ACTA UNIVERSITATIS SZEGEDIENSIS

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CURAT: G. KOPPÁNY

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Contents

On Heat Death in Past, Present or Future

by B. LUKÁCS

Central Research Institute for Physics RMKI H-1525 Bp. 114. Pf. 49., Budapest, Hungary

A lot of paradoxes have been invented about the time evolution of the entropy of the Universe. A family of them is called Heat Death, and on the basis of these paradoxes it was often doubted if the entropy of the Universe can at all defined, or if it can, would it obey the Second Law, &c. Indeed, Universe is an exceptional system (solitary, no neighbourhood, no conservation of energy) and therefore the concept of the entropy of the Universe needs some caution. Also the history of this entropy is complicated. The present paper discusses these problems.

A hőhalálról múltban, jelenben vagy jövőben. Paradoxonok sokaságát állították már fel az Univerzum entrópiájának időevolúciójáról. Ezeknek egy családját hőhalálnak nevezik és ezen paradoxonok alapján gyakran kételkedtek abban, hogy lehet-e egyáltalán az Univerzum entrópiáját definiálni, vagy ha lehet, engedelmeskedni fog-e a Második Törvénynek, stb. Valóban, az Univerzum egy kivételes rendszer (társtalan, nincs szomszédsága, nics energia-megmaradása), és ezért az Univerzum entrópiájának fogalma bizonyos körültekintést igényel. A története is bonyolult ennek az entrópiának. A jelen tanulmány ezeket a problémákat vitatja meg.

1. Introduction

Paradoxes constitute a *negative* of collecting knowledge. At a given stage of the science have a given amount of knowledge; some correct, some not. Then we try to find out the result of a Gedankenexperiment. A paradox is found if two different results can be obtained by seemingly correct and consequent derivation, or if the only result is impossible or contrary to common sense. Paradoxes are signals that *something* is wrong: either our present theories or data (which is always possible) or our common sense (which is the essence of our previous experiences). Paradoxes are not to be taken too seriously; they do not indicate onthological problems. However they are to be kept in mind, because until they are not solved, something must be wrong.

A famous old paradox of cosmology was Heat Death. In the present decades it is rather forgotten, and indeed it has been *partially* solved. But not fully, and it is worthwhile to remember it from time to time.

Heat Death was originally formulated in the last century. After establishing the first two Fundamental Laws of thermodynamics it seemed that they contradicted each other when applied on the whole Universe. For a closed system the First Law states the conservation of energy, while the second the equilibration or by other words the monotonous increase of entropy. The conservation indicates infinitely long past and future of the Universe. But if so, then the entropy should have reached (or asymptitically approached) its final value and been utterly equilibrated (rotten or corrupted) which is not so. Here was the paradox.

Many attempts were made to solve it. But, as again and again turned out, the thermodynamics of the *whole* universe needs extra caution. Namely, the Universe (if such a definite entity exists at all) palys the role of the proverbial sick horse of veterinarian courses. It may be infinite; it is thermodynamically not closed even when it is a closed hypersphere; the energy is not conserved in it; and so on. In this paper we show up several problems and try to give the solutions if available. We shall see that we do not know to give a complete description of the thermodynamic evolution of the Universe from a very exotic (singular?) past to the possibly infinite future. However our present knowledge about the ultimate past and future is hazy enough to be able to *imagine* ways out of the paradox.

2. The pre-Friedmannian era

The classical explanations were various, diverse and not statisfactory. The simplest one stated that is ill-founded to extend the thermodynamics of finite systems to the infinite Universe. Either because the latter is not a *closed* system, or because it is not *macro*scopic but *mega*scopic.

However consider a Universe homogeneous on large scale (to be conform with the cosmological principle). Then there is no net currrent between any two sufficiently large neighbouring parts and then these parts are as if they were physically closed. Remember this for later use. So infinity in itself does not help.

The appeal to megascopy was more philosophical. It is a popular idea to classify objects onto three levels in sizes, masses, particle numbers or anything else, with disjoint laws on each level. The first such level would be microscopy, i.e. the „atomic" level, the second macroscopy, which is our own level, and the third megascopy starting somewhere at very large astronomical systems and „ending" with the global Universe. For example Poincaré guessed [1] that the random motion of *planets* is not analogous to that of *molecules*; while the second is undoubtedly heat, the first is rather mechanical work because of the larger sizes and distances.

Such a trichotomy is by no means impossible, since our present laws are approximate. Indeed, such a separation of levels was the popular solution of the measurement paradox of quantum mechanics, although now it seems that it is not hopeless to derive the different behaviours from common laws [2], [3], [4], [5]. For a recent review about possible levels see Ref. 6. However never anybody observed astronomical processes making the entropy decrease. And if one fundamental law of thermodynamics ceases to exist above macroscopic level, why just the Second Law, why not the First, for example?

Eddington suggested a solution completely possible but very disturbing. In the past of an infinitely old system *any* kind of thermodynamic fluctuations must have happened, the larger the rarer. Life and intellect become possible sufficiently far from equilibrium, so we can exist only not too long after a sufficiently large fluctuation; therefore the extreme rarity of such an event is not incompatible with the fact that we observe its consequences. When a very large fluctuation happens, afterwards somebody comes into existence and observes that Heat Death is still far ahead; when the system have returned to near-equilibrium and the paradox does not appear, nobody exists to be contented. This was the strongest classical solution. However with the advent of General Relativity the whole context changed.

3. The Friedmannian past singularity

Einstein introduced the idea that the (geometrical) laws of the space-time are governed by the matter in it. Ignoring all the details, there are 3 and only 3 geometries for the space-time which are homogeneous and isotropic in space. They are the **Robertson—Walker** Universes [7], namely

$$\begin{aligned} ds^2 &= dt^2 - R^2(t)\,\{dx^2 + F^2(x)\,d\Omega^2\} \\ d\Omega^2 &\equiv d\Theta + \sin^2\Theta d\Phi^2 \\ F(x) &= \begin{cases} \sin x & \text{if } k = +1 \\ x & \text{if } k = 0 \\ sh\, x & \text{if } k = -1 \end{cases} \end{aligned} \tag{3.1}$$

Henceforth the time units are such that the light velocity c is unity. The sign constant k is called space curvature. The $k = +1$ Universe is closed, the 3-surface of a 4-hypersphere of radius R (and then the full volume is $2\pi^2 R^3$); the other two geometries are open spaces and $R(t)$ is a scale length of the geometry. Therefore the global geometry is determined by the sign constant, while the local curvature can change according to R.

From the Einstein (or **Einstein—Hilbert**) equation of gravity, for this geometry filled with a homogeneous fluid matter one gets two evolution equations. They can be written as

$$\dot{R}^2 = -k + (8\pi/3)GR^2\epsilon \tag{3.2}$$

$$\dot{\epsilon} + 3(\dot{R}/R)(\epsilon + P) = 0 \tag{3.3}$$

where ϵ is the energy density and P is the dynamical pressure.

This system of equations is not closed. A further relation would be needed among R, ϵ and P, whose simplest form is an equation of state $P = P(\epsilon)$ say in local equilibrium. Then the equations can be integrated and there remain only a few constants of integration in the solution. For demonstration we give here the solution in the simplest case: $k = 0$ and $P = 0$ *(dust)*. Then

$$R = W(t - t_o)^{2/3} \tag{3.4}$$

$$\epsilon = (1/6\pi G)(t - t_o)^{-2} \tag{3.5}$$

Here two constants of integration appear, but W can be made 1 by rescaling the coordinate x as seen from eq. (3.1) for $k = 0$. The other constant is simply the startpoint of time counting and it can be made 0 by a convention.

Now observe that this solution has a singular moment when all the distances are 0 and the density is infinite. One cannot uniquely continue the solution through a singularity. First **Friedmann** gave the dust solutions for all the three k's: all contain somewhere a singularity and for $k = +1$ singularities are periodic in time. So the history either starts or ends with a singularity or happens from singularity to singularity. With pressure the history may be complicated, but the **Hawking-Penrose** singularity theorems [8] predict past or future singularities for a very wide class of equations of state.

The galactic redshifts indicate $R > 0$ for the present, this means the existence of a *past* singularity; the future one is doubtful, since it exists only for $k = +1$. Then the Universe is not infinitely old; the estimated age from redshifts is cca. $15 \cdot 10^9$ years, in rough accord with observed chemical compositions &c. Therefore it seems that the paradox does not exist anymore.

This is not quite sure. The so called *horizon problem* [9] states the fact that from the Beginning in a standard cosmology no physical signal could have traversed betwen some remote parts of the Universe now observable for us, and in spite of this they have e.g. the same temperature. Sometimes an infinite quantum prehistory is suggested at **Planck** density $\epsilon \sim (c^7/\hbar G^2)$ where the gravitational law is unknown enough for the existence of a static solution [10]. But then returns the infinite age and past Heat Death. And the future fate remains anyways a Heat Death, except for the finite future of the $k = +1$ closed Universe, which, in turn, ends with a catastrophe. So, independently of the past, it is worthwhile to discuss the infinite future of the $k = 0$ and -1 Universes. According to scientific folklore they asymptotically go to a Heat Death. The remaining part of this paper is devoted to the question if this asymptotic Heat Dying is the necessary fate or not.

4. On the Pfaffian form of thermodynamics

Some years ago my attention was called to the fact that even without the past singularity and finite age the Heat Death paradox would not be necessary [11], from at least two different thermodyynamic reasons. The first one is very simple. For simplicity, consider a closed $k=+1$ Universe. It is not a closed system *in thermodynamic sense*. Namely, a thermodynamic system is closed if *all* its independent extensive quantities (volume, energy, particle numbers &c.) have constant total values in it. However, in our Universe R is increasing. So for the *whole* Universe V is not constant. If a thermodynamic system is not closed, then the Second Law does not guarantee the entropy growing, and, furthermore, it does not guarantee that the possible maximum of the entropy be a finite constant. In our case the total entropy may grow in the growing volume, but not necessarily will asymptotically approach a final value. We will return to this point later.

The second thermodynamic complication is even more interesting, and it would have operated even in the infinite Euclidean Universe of the last century. Therefore now let us concentrate on this point. It is interesting to contemplate why it did not appear as a solution in the earlier literature. My guess is that this was caused by a historical accident. Namely, the remark states the fact that the existence of irreversibility in thermodynamic processes does *not* a priori guarantees the growth of entropy for more than two independent extensives, and volume, energy and particle number are already at least three. If the Caratheodory construction had been made *before* the General Relativity, then this solution should have appeared in the discussions.

Thermodynamics is the physics of irreversibility, say, the irreversibility of energy transfer. Consider a thermodynamic system with the independent extensives X^i, $i \leq n$. In the familiar systems these extensives are the volume V, *internal* energy E, various particle numbers N^r, &c. There seems to be no problem with the definition of V or N; the internal energy E needs some considerations because it is not necessarily the total energy, but now let us first assume that it is already defined.

Let us move infinitesimally in the state space $\{X^i\}$ by adding some amounts of the extensives to the system. Then there is a dE; some part of it is reversible, some not. Let us write then the decomposition

$$dE = \eth W + \eth Q \tag{4.1}$$

the first is the *mechanical work*, the second is the *heat transfer*. Generally nonr of them is an infinitesimal of a function Q or W, this is the reason for the notation $\eth$.

Now we are interested only in the *irreversible* part. In arbitrary processes of course $\eth Q$ can arbitrarily change. However, define a *special* kind of isolation called *adiabatic* (say, no „heat" transfer) and require that such processes have some irreversibility. The irreversible nature of infinitesimal *adiabatic* processes can be formulated by

$$\delta Q \geq 0 \tag{4.2}$$

(„non-compensated heat"). For a given system of course the structure of δQ is fixed:

$$\delta Q = Z_r(X^i)dX^r \tag{4.3}$$

where and throughout the whole paper the Einstein convention is followed, i.e. there is summation for indices occurring twice, above and below. Then with the actual form of the functions Z_i (characteristic for the actual system) (4.3) can be reduced to one of the canonical **Pfaffian** forms [12]:

$$\begin{array}{ll}
\delta Q = dQ(X^i) & K = 1 \\
\delta Q = T(X^i dS(X^i) & K = 2 \\
\delta Q = dU(X^i) + T(X^i)dS(X^i) & K = 3 \\
\delta Q = H(X^i)dU(X^i) + T(X^i)dS(X^i) & K = 4
\end{array}$$

and so on, $K \leq n$. *The* $K = 2$ case is the usual thermodynamics A tedious but straightforward derivation [12] results in the following statements:

For $K \leq 2$ Cond. (4.3) leads to *global* irreversibility, namely generally between two points of the state space (except on a hypersurface of 0 measure) adiabatic processes can go only in one direction and not back. However it is not quite so for $K \leq 3$. There between *any two* points one can go on one path forward and on another backward. So now the irreversibility of elementary steps $\delta Q > 0$ does not result in global irreversibility and perpetua mobilia of second type are possible.

The complete proof is in Ref. 12. However a rough argumentation goes as follows. For $K \leq 2$ (if the functions T and S have unique values and do not change signs) $\delta Q > 0$ means increase of S, so different points in the state space. But for $K = 3$ $\delta Q > 0$ does not necessarily indicate anything monotonous in S and U.

Now a number of experiences point against the existence of perpetua mobilia. Postulating their nonexistence $K \leq 2$ follows and the existence of nontrivial temperature rules out $K = 1$. Therefore $K = 2$, and then we arrive at **Caratheodory's** thermodynamics [13].

However this, and therefore the increase of the entropy, is based on the nonexistence of perpetua mobilia. If this leads to a paradox and the final result is unacceptable for somebody, he may assume that $K \geq 3$ (if the number of independent extensives is ≥ 3), only $\partial Q \approx TdS$ in a good approximation under macroscopic usual circumstances.

Since the expanding Universe the matter is more and more diluted and no exotic behaviour is predicted, we do not want to propose this as a solution of the paradox *in the future*. However, a $K \geq 3$ Pfaffian form may have been valid in the quantum past of the Universe, of which we know nothing at all [14].

Henceforth we *assume* that $K = 2$.

5. Is the growing thermodynamic entropy unique?

So let us assume that the entropy S cannot decrease in a closed system (or in adiabatic processes). Then, as we saw in the discussion of the Pfaffian forms, S is a function of the independent extensives, therefore

$$dS = (\partial S/\partial X^i)dX^i = Y_i(X)dX^i \tag{5.1}$$

where Y_i are the entropic intensives. In axiomatic thermodynamics these intensives possess equal values in the equilibrium of two different systems. Since Y_i are the partial derivatives of S, therefore if we know the form of the single function $S(X^i)$, we know the full thermodynamic behaviour of the system [15].

However one cannot a priori know the S functions. By pure thermodynamic measurements one may try to determine the S_α functions observing extensive values X_α and X_β at equilibria $Y_\alpha = Y_\beta$. For ν different systems this sequence of measurements imposes $1/2\nu(\nu-1)n$ relations on the νn partial derivatives, so at sufficiently high ν one expects even overdetermination, and if not, then unique entropy functions. However it is not so. For $\nu > 3$ no further independent relations are obtained [16], and thermodynamic measurements cannot completely determine the function $S(X^i)$.

The maximum of determining it is the freedom [17]

$$S_\alpha (X^i) \rightarrow K^2 S_\alpha(X^i) + C_r X^r \tag{5.2}$$

where K and C_i are *universal* constants. Indeed, such a change of gauge rescales and shifts the corresponding intensives of *all* systems in a synchronised way and the equilibria remain equilibria. So the thermodynamic entropy is not unique.

Henceforth for simplicity we restrict ourselves to systems with 3 independent extensives, V, E and N. Then the freedom is

$$S_\alpha \rightarrow K^2 S_\alpha + AV + BE + CN \tag{5.3}$$

Then it is easy to see that even statistical physics does not help. E.g. **Boltzmann's** H theorem singles out such $H = -S/V$'s, whose changes are monotonous. Now in a closed system V, E and N are fixed, so they do not influence monotonous changes. Similarly, e^S is proportional to statistical weights, but the transformation (5.3) do not alter the **Riemann** geometry of the state space [17], so e.g. fluctuation probabilities are invariant [18].

In a closed system (5.3) is irrelevant. However in a Universe where V changes because of expansion and E because of energy nonconservation, the change of S depends on the choice of the actual S. With an „appropriate" A it is even possible that one S increases and another decreases.

In Ref. 19 we suggested that the universal constants A, B &c. should be determined by observing the Universe. This way is possible, because the *thermodynamic* pressure p

$$p = (\partial S/\partial V)/(\partial S/\partial E) \tag{5.4}$$

depends on A and B. By assuming that the thermodynamic pressure p is the leading term of the dynamical pressure P of the matter filling the Universe, and taking some probable Ansatz for the matter (say, ideal gas), A and B influence the scale function of the Universe $R(t)$, so from the observed expansion A and B can in principle be deduced. At present the best available constraints are:

$$\begin{gathered} -10^{6}\ cm^{-3} < A < +10^{+3}\ cm^{-3} \\ 0 < B < 10\ MeV^{-1} \end{gathered} \tag{5.5}$$

where $A = 0$, $B = 0$ belong to the „naïve" gauge (say, $p = nT$ for ideal gas, &c. [19].

So if we are fanatic to know what is the fate of the entropy of the Universe, we can determine first which is the its most proper entropy. But it is always told that the Caratheodory construction leads to unique entropy and temperature. What is then this variety of entropies?

6. On the decompositions of heat and work

Observe that thus far we have postulated only the *existence* of irreversibilities in thermodynamics. Since we are interested in the ultimate fate of the whole Universe here, some efforts must not be spared and one ought to take as little in face value as possible. So: we do not see perpetua mobilia of second type, although they have been looked for very hard. So thermodynamics seems to have *global* irreversibilities. However, in a system any wanted state can be prepared by adding or subtracting just the proper amount of energy, particles &c. to or from a system. So it is rather hard to formulate ireversibility or an *open* system; and of course it is impossible to do for a *closed* one, since extensives do not change at all in such ones. Then we require an inequality

$$\partial Q \geq 0 \tag{6.1}$$

for changes in *adiabatic* systems as told in Sect. 4. Adiabatic isolation means roughly „no heat transfer" or „only mechanical work transferred" [12], but at this point neither heat nor thermal energy have yet been defined, so it would be better to find a physical limiting procedure towards adiabatic isolation.

Now, let us accept a well motivated such limiting procedure. Then we can perform experiments to check the predictions of the formalism. We have a container as adiabatically isolated as possible or needed. The internal energies of states can then be mapped via a **Joule**-type experiment. Take a state $V = V_o$, $E = E_o$ (this is an arbitrary definition for an initial point), $N = N_o$. Adiabatic walls permit only mechanical work to be transferred, and no „heat" can leave the system. Then let some mechanical work be injected into the fluid in the container. After some time internal turbulences vanish. The total volume and particle number remained unchanged, so only E can change. Therefore the only possibility is $\partial E = \partial W$, and ∂W was measured outside. So we define the internal energy of the new state as $E_o + dE$, and if this in equilibrium with another piece of the same matter then E/V is the same that too.

Now we know V, E and N in any specific state, and we *know* that $\partial Q = T(E,V,N)dS(E,V,N)$ must hold, otherwise perpetua mobilia would exist (the Pfaffian form $K = 1$ is a special case here with $T \equiv 1$). This means a *foliation* in the space $\{E, V, N\}$, i.e. that the function S has a unique value at any point [12], and then for adiabatically isolated systems we are at the Second Law. Adiabatically isolated systems continuously climb up from layer to layer in S.

This S must be the entropy mentioned in the thermodynamic axioms [15] because that is the quantity with the tendency of growing in closed or adiabatic systems. That we know how to measure (see Sect. 5). There remain some freedoms in it, but they do not influence the foliation since the additive terms cannot be multivalued. So from the Pfaffian form all of them may be entropies; if other principles rule out some of them, the fewer the better.

Now we can start with the checking process. If indeed we see the foliation in S, everything is settled. But what if we see something else? Then something fundamental must be wrong. It cannot be in the Pfaffian form since no perpetuum mobile is seen. It cannot be in the determination of the internal energy, because that process is unique. There remains a single possibility. Either the 3 variables $\{E, V, N\}$ are insufficient for description, which is theoretically possible, but only a technical problem, or the physical limiting process of adiabatic isolation was improper. Since there *is* global irreversibility, there must be at least one construction for adiabaticity which at the end will result in good foliation.

Let us stop briefly at this point. It seems as if we had a full-proof construction. Take a container with strong, thick and rigid walls, with a negligible hole and turbine inside. A rope through the hole connects the turbine with a weight outside. By the rope we can put mechanical work into the container and if the walls are more and more substantial, nothing is expected to leave the system, so no heat either, anything be heat. This is the naïve idea about a limiting Joule experiment, and it sems unique.

However, *this limiting procedure is not necessarily unique*, because

ad 1) one cannot guarantee that *nothing* leaves the container even with infinitely thick isolating walls, remember e.g. gravity which cannot be shielded;

ad 2) infinitely thick walls of a finite container can absorb finite amount of, say, energy, without even the possibility of detecting the absorption, i.e. if nothing comes out, still something may leave the sysytem under investigation.

Therefore there is no guarancy that the definition of *adiabatic* isolation compatible with global irreversibility would be unique. If not, different possible definitions result in different, but equally possible thermodynamic descriptions of systems. And the same is true for the freedom (5.2).

However, even then infinitely many description are ruled out. This means that indeed the existence of global irreversibilities prescribe how to decompense the energy transfer dE into heat transfer δQ and mechanical work δW. And remember that for $K = 2$ Pfaffians there is no function $Q(E, V, N)$ which would yield dQ as differential. For $K = 1$ it would exist and would coincide with the entropy; then the temperature would always be the same constant. According to everday experiences of the last centuries, this is not the situation.

In cosmology the large scale homogeneity guarantees that no net current of *anything* physical can go between two great expanding parts of the matter. Therefore we can be sure about the lack of current of internal energy even before defining the internal energy. Then there may be a physical limiting process for adiabatic isolations, because no walls are involved. If so, then the Universe can define its natural thermodynamics.

7. Can entropy really approach its final value in a closed system?

In this Chapter we take a finite amount of the matter of the Universe, put absolutely isolating walls around (which do not necessarily exist, but that comes in the next Chapter), and ask, what will happen. The folklore tells that the entropy of that piece of matter will asymptotically go to its maximal value. There is no proof *against* this belief, but an example will demonstrate that it is not necessarily so.

Imagine a container of volume of some liters, made from indestructible material, with a realistic internal partition (say a thin sheet-iron). Put some indestructible detectors inside, and say, one mole of oxigen to the left and two moles of hydrogen to the right, if you like, with some amount of catalysers. Since the container is indestructible, it is the same if you bury it or not. The detectors are continuously detecting, what will be seen by the sequence of generations?

Our knowledge is finite in this moment. According to this finite knowledge the story goes as follows.

Step 1: Possible initial temperatures equilibrate by heat conduction, even through the partition. Time: seconds, increase in specific entropy: say *01*.

Step 2: At the same temperature there is a pressure difference between the two sides of the partition. The difference is slowly bending the sheet-iron. After, say, weeks the partition is bent in such an extent that volume changes equilibrate the pressures. The specific entropy has gone up by ~ 1.

Step 3: After that chemical potentials are still different on the two sides, since on the left there is no hydrogen, on the right no oxygen. But in a time between a year and a millenium the sheet-iron gets rusty and perforated (evidence: archeology). Through the holes the gases diffuse and completely fill the whole container. Specific entropy goes up by ~ 1. Now all the intensives have become spatially homogeneous, so one would expect that the entropy is already maximal. However it is not.

Step 4: H und O can be combined into H_2O, and they are being, with a rate depending on temperature and catalysers. So as time goes by, there will be *three* kinds of molecules, H_2, O_2 and H_2O, each with its own chemical potentials, and, say, in hundred thousend years they equilibrate as

$$\mu_{water} = \mu_{ox} + 2\mu_{hyd} \tag{7.1}$$

Again entropy went up by ~ 1. *The story ended here for a physicist in 1890.*

Step 5: Nuclear fusion still can go. Without catalysers cold fusion takes a time much longer than billion years and according to the present stage of knowledge no efficient catalyser of cold fusion is known (the palladium has not been proven sufficient). However the container is everlasting. So at the end the matter is a mixture of electrons and various nuclei, mostly Fe^{56}, with the equilibria

$$\begin{aligned} \mu_{He} &= 4\mu_H \\ \mu_{Fe} &= 56\mu_H \\ &\&c. \end{aligned} \tag{7.2}$$

With the differences of rest energy deliberated the temperature goes up to ~ billion K; the specific entropy again went up by ~ 1. *Here ended the story for anybody in 1960.*

Step 6: Grand Unification predicts proton decay e.g. according to the scheme $p \rightarrow e^+ + \pi$. Experiments are going to check it. If so, in a time $\sim 10^{32}$ years most nuclei vanish, and the remainders equilibrate according to eq. (7.2) and to a new equation

$$\mu_H + \mu_{e+} \tag{7.3}$$

Again the specifiv entropy went up by ~ 1, *and the story ends here for us at the present.*

But a new step has been conjectured since 1960. Therefore nothing rules out new steps to be discovered. The scheme was roughly the same increase of specific entropy at the appearance of each new degree of freedom. In an infinite time will there be finite or infinite such steps, will the final entropy be finite or infinite?

Ignoramus et ignorabimus. In finite time we can discover the possibility of finite steps, so the *actual* answer is always finite. But this does not prove anything. One could argue that after proton decay there is not too much remaining rest energy to thermalize. However *note that this rest energy was unknown in 1890, therefore everybody would have used the same argument against further entropy production beyond Step 4.* We do know energies beyond rest energy, say the zero pont fluctuation of quantum electrodynamics. The present theories do not suggest anything for ways of deliberating this infinite energy, but this is not necessarily the final stage of knowledge.

Therefore we cannot definitely decide if there is a (finite) maximum of the entropy of a closed container or not. If not, the entropy may grow forever, without reaching any maximum even asymptotically. Of course, it is possible that the entropy increase is *practically* nil for aeons.

8. Can closed containers physically exist even as limits?

Here we very briefly show an example when the favourite closed systems of thermodynamics are physically impossible under some circumstances. Our example is the quantum field effect of the expansion. Only the results are mentioned; for the details see Ref. 20 and citations therein.

Quantum field theories in their present forms are not necessarily compatible with General Relativity. However they can be used in a curved time-dependent geometry, e.g. in the metric (3.1), and then one gets a time-dependent nonzero energy density even for the vacuum. It is very roughly similar to a thermal radiation with

$$T \sim \hbar\dot{R}/R \tag{8.1}$$

One may visualize the result in the way that in a changing geometry everything is excited at least by the specific energy (8.1).

Then this energy will appear even in a closed container. One may tell that such a container is not closed. However the effect causing the energy to appear is the change of the metric, and this is called colloquially gravity. Gravity cannot be shielded because of the equivalence principle. Therefore if geometry is changing, here are no containers of fixed volume in which the energy of the system could be kept constant.

This is a situation in which we *know* thet no complete isolation is possible, which was conjectured in Chapter 6. Still the thermodynamic formalism can work. One may, of course, have some doubts about a formalism based on physically impossible abstractions. But this a question deserving lengthy and elaborate discussions. For the present we may remain at the usual thermodynamics.

9. The lack of conservation laws

A *closed system* is a system in which E, V and N are constant. This is a thermodynamic definition, but there are some beliefs that E and N should be conserved in a properly circumwalled system. Let us first concentrate on E.

The previous Section showed an example when no physically possible walls can keep the energy constant. But Sect. 6 mentioned that in the Universe it is possible to single out a container withouf walls which is absent of currents crossing the borders. Such a „container" is a part of the Universe, whose fictitious borders were drawn at some t_o and afterwards follow the expansion. So, due to complete spatial symmetry no net current flows through the borders. Now V grows, so the system is not *closed* in thermodynamic sense, but at least there is no *transfer* of E. However, if there is no energy *current*, still there may be energy *source*. And indeed, there is. Consider eq. (3.3). Thence

$$(\epsilon V)^{\cdot} = -P\dot{V};\ V \equiv V_o(R/R_o)^3 \tag{9.1}$$

Therefore the volume integral of ϵ, which cannot be anything else than the internal energy E, is definitely not conserved.

Eq. (9.1) is *not* some new result of General Relativity; it is the usual equation of hydrodynamics, or can be written as $dE + PdV = 0$, which is the usual formulation for *quasistatic* adiabatic processes. However, outside the scope cosmology matter configurations have boundaries. For a volume extending beyond the boundaries in the source equation $P = 0$ (vacuum) and then the total energy is conserved. But in Universe P is homogeneous in space, therefore one cannot take volumes with conserved energy. The only exception is if the pressure is everywhere 0, i.e. all the matter is without any interaction. The present Universe is fairly close to such state, but this statement is not general at all.

As for N, various particle numbers exist, some do not seem conserved, some do. However, from time to time it turns out that a particle number is only *approximately* conserved. E.g. in the $SU(3)\cdot SU(2)\cdot U(1)$ Standard Theory of particle physics there are 3 conserved charges: baryonic number B, leptonic number L and electric charge Z. (In fact, B and L are conserved for three disjoint families.) In the $SU(5)$ simplest Grand Unification, however, B and L are not conserved separately, only $B - L$. The corresponding predicted effect is the proton decay, for which experiments are still running; with no clear result, but the predicted lifetime is very long under present circumstances. So we cannot a priori know which particle number is conserved and which is not.

In addition, according to any knowledge, for large comoving volumes of the Universe $Z = 0$, and it is not impossible that $B - L = 0$ as well. If so, then the conserved numbers take trivial values in the Universe.

10. The final enumeration of doubts

Let us try to describe then the thermodynamic evolution of a large expanding volume of the Universe. There are no currents. The isolation seems adiabatic. Global irreversibilities then must appear. However there is not a single closed system in the whole description. V is growing, E is changing and maybe a lot of N's as well. Then what will happen with S in such an autonomous volume?

The answer is by no means trivial. From pure thermodynamic viewpoint it is not too important either: what is important that is the global irreversibility. It may seem paradoxical again that S might decrease with irreversibility, but the system (or the whole Universe, either) *is not closed in thermodynamic sense.*

The simplest demonstration can go through the transformation (5.3). Consider a model Universe of perfect fluid; no viscosity, no nonequilibrium processes, &c. Then one expects $S = 0$. But if so, after the transformation S can grow or decrease according to the actual values of the constants A and B.

Still in such cases one can keep $S \geq 0$ if the particular entropy is chosen in accordance to the thermodynamic leading part of the hydrodynamic pressure (remember Sect. 5). Indeed, this entropy, and therefore the corresponding specific values of the free constants in the tranformation (5.2), are not selected by Thermodynamics, but by the Universe. It would deserve some further study if such an entropy can always be selected even for general kinds of matter.

Note that with an increasing energy growing entropy of course does not necessarily implies asymptotic equilibration. Consider some temperature inhomogeneities in the system. Some energy flows from the hotter place to the cooler one, so there is energy transfer inside the system. However if energy is being produced, then it is by no means impossible that in spite of the transfer the difference is maintained by the new energy. Since in some cases the energy production is proportional to the entropy production [21], some pattern-forming processes analogous to those in the thermodynamics of open systems may have appeard in the early vehement stages of evolution.

11. The possible fates of Universe

First about Beginning. For the Universe, being unique, it would be better not to have the freedom of initial conditions. There is a hope for such a unique initial condition. In the unified theory of Gravity, Relativity and Quantization Planck data formed exclusively from G, c and $\hbar$ would be unique and would describe natural „elementary" objects or states. Such a unified theory is not at reach, although supergravity or superstring theory may be fair attempts to get at it.

Even incomplete unifications may show up „natural initial conditions". It was mentioned in Sect. 3 that static solutions might exist and can be got from „semiclassical approximations" at Planck density 10^{93} g/cm^3 and Planck radius

$$R_{Pl} \sim (\hbar G/c^3)^{1/2} \sim 10^{-33}\ \mathrm{cm} \tag{11.1}$$

[10]. Another example is to incorporate Hawking radiation into the thermodynamic description and energy-momentum tensor [20]. In some models then the past of the

Universe becomes geodesically incomplete, and suddenly appears with a radius in the order of R_{Pl}. Until we get the complete theory, we can *hope* in natural initial conditions.

However in that stage within the volume $\sim R^3$ the total entropy was ~ 1. Now $S/N \sim 10^8$ (deduced from data of the 3 K black-body radiation), and R seems to be $\gtrsim 10^{28}$ cm. Therefore $S \sim 10^{87}$ [9]. So, if the natural initial conditions were true, very strong entropy production must have happened in some early stages. In accordance with this, originally E in a volume $\sim R^3$ was $\sim E^{Pl} \sim 10^{16}$ erg, and for radiation-dominated Universes eq. (9.1) would imply *decrease* of E, while now it seems to be 10^{53} erg. E can have increased only with *negative* P. Luckily, some irreversibilities make P decrease. A variety of models with substantial negative pressure and roughly exponential expansion was invented (see e.g. Refs. 9 and 22); this stage may have happened at $t \sim 10^{-35}$ s, 10^{28} K temperature. Afterwards the Universe may have undergone a lot of phase transitions, irreversibilities &c. [23], but for bulk properties the evolution was not too different from that of a simple radiation-filled Universe.

Radiation dominance ended at a time when the radius was $\sim 10^{-3}$ of the present one. Afterwards gravity could form density inhomogeneities, evolving through steps of fragmentation. The final step is contraction into stars; they start to produce energy in nuclear fusion, and then contraction stops. For stars above several solar masses this equilibrium is only temporary, after say 10^9 ys the nuclear fuel is exhausted and the star collapses; some part shrinks into singularity and the periphery is ejected. However less massive stars can remain in equilibrium as white dwarfs or neutron stars „forever".

Therefore more and more matter is put away in compact cold objects, therefore stars become more and more dispersed. This more or less resembles the Heat Death of the last century. However the *ultimate* fate depends on the sign constant k in eq. (3.1).

For $k = +1$ the Universe is spatially closed. Such models with simple pressure laws always result in a recontraction. Present observations are not yet enough to decide the value of k, but even if $k = +1$ we cannot be close to the recontraction. Rough estimations indicate at least 50 billion years future; towards the end of this period practically all the stars will be minute red dwarfs under half solar mass. At the end the recontraction will dissolve all the structures. All guess-works of calculation suggest that at the end S will be in the same order of magnitude as now (except if in the new quantum density era a $K > 2$ Pfaffian form develops and then emerging perpetua mobilia decrease back S to its natural value ~ 1, ready for a new cycle.

For $k = 0$ or $k = -1$ all known models predict expansion forever. Forever is a serious word and our finite present knowledge is insufficient to calculate forward for infinite time. However we can predict for finite times: the longer the less safe. Again, stars are dying. After some say 10^{12} ys there are practically no shining stars, no temperature gradients. However still there are cold compact objects, so there are serious gradients in chemical potentials. They cease to equilibrate because cold neutron stars and blackened dwarfes are gravitationally bound objects. During that period S remains practically the same as now.

However, *if Grand Unification is correct*, the number of the present protons will be halved at 10^{32} ys from now by proton decay. That is almost total conversion of the proton mass, so S will go up (according to a very rough estimate) by a factor ~ 1000. This means reappearance of temperature gradients as well at the decaying stars. (These gradients will be much more moderate than the present ones: energy deliberation rates of stars will then be 10^{-20} times the present ones.) The increase of temperature gradients will not contradict to the Second Law: in the same time the chemical potential gradients decrease because of the disappearance of baryons. This will be an excellent example of cross effects of equilibration.

Afterwards there will be no stars anymore; the resulting positrons will annihilate with the electrons. Bound configurations of massive neutrinos may remain if neutrinos have mass at all. There is one more predicted energy producing process on longer time scales and that is the Hawking radiation of black holes; for the smallest black holes created in astrophysical collapses this time scale is very roughly 10^{60} ys, but the existence of such a radiation still would need confirmation from the unified theory. Even if it existed, it would leave S in the same order of magnitude.

Beyond that time present theories do not tell anything; remember Sect. 7.

12. Conclusions

This paper is bold enough to discuss ultimate questions even if only about entropy. Therefore there is great chance fot mistakes. However we can draw the conclusions that i) there is no a priori reason to be sure about the possibility of a Caratheodory-type entropy construction for the Universe in its whole life, but ii) if good arguments (as e.g. well-founded lack of perpetua mobilia of second type) exist for it then the entropy of the Universe can be defined; iii) this entropy will then be thermodynamically quite regular, but its evolution may be influenced by the fact that the Universe is not a closed system in thermodynamic sense. In addition, the Universe may have infinite future and iv) one cannot guarantee the finite final value of the entropy for infinite times even in a closed system.

As for the future of Universe, a story can be and has been told, but one cannot correctly predict for infinite times.

Acknowledgements

Detailed discussion with the late Dr. G. Paál are acknowledged. Some ideas in Sect. 4 were suggeste by Dr. K. Martinás,, and specially Sect. 6 was planned originally in discussions with her as a part of Ref. 19, but in both cases she has declined to participate in the work. Therefore both Sections contain some remembrances of private communications, but I must take all responsibilities for the present formulation and conclusions.

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Temperature Variations in Europe and North America since the Beginning of Instrumental Observations

by G. KOPPÁNY

J. A. University, Szeged, Egyetem u. 2. H-6722, Hungary

With the intention of an analysis, *19* climatological stations have been selected which are in possession of an annual mean temperature series longer than two hundred years (*Table I*). The running 9-year mean temperatures have been used in order to determine the coincidences of the warmings and coolings at different stations in central, western and northern Europe, as well as in the eastern USA. Several short periods were found with simultaneous maxima or minima in many different locations. Comparing these periods with volcanic activity, it is pointed out that the temperature minima are close to high volcanic activities, and temperature maxima to calm volcanic episodes. It has been also found that in *8* stations out of *18* temperature maxima before *1880* were higher than those after *1880*. It is likely that the global mean temperature had relatively low value around *1880*.

Hőmérséklet-változások Európában és Észak-Amerikában a műszeres észlelések kezdete óta. 19 klímaállomást választottunk ki elemzés céljára, amelyek kétszáz évnél hosszabb évi középhőmérsékleti sorozattal rendelkeznek (*I. táblázat*). A hőmérsékleti adatok *9*-éves simított értékeit használtuk, hogy meghatározzuk a melegedések és lehűlések egybeesését különböző állomásokon Közép-, Nyugat- és Észak-Európában, továbbá az USA keleti részén. Több olyan rövid időszakot találtunk, amelyeket a különböző helyek egyidejű maximum vagy minimum hőmérséklete jellemez. Összehasonlítva ezen időszakokat a vulkáni tevékenységgel, kimutatható, hogy a hőmérsékleti minimumok erős vulkánossághoz, a maximumok csendes vulkánossághoz közeli években fordultak elő. Megállapítottuk azt is, hogy *18* állomásból *8*-ban *1880* előtt a hőmérsékleti maximumok magasabbak voltak, mint *1880* után. Valószínű, hogy a globális középhőmérséklet *1880* körül viszonylag alacsony volt.

Introduction

It is widespread known, that the global mean temperature of the Earth has increased by cca *0·5* K since *1880*-s (**Lockwood, 1986**; **Götz, 1983**; **Brazdil, 1987**). The warming has been as much as *0·8* K in the northern hemisphere, and reached its peak in years *1938—40*. Hence many authors concluded, that this warming is the response of the atmosphere to increasing CO_2 after beginning of industrialisation and technical development from late *19*-th century (**Energy and Climate, 1977**; **Budyko, 1982**). Moreover according to numerical climate model experiments the global warming may reach *2—5* K by *21*-st century, if the increase of atmospheric CO_2 will continue with present rate (**Bach, 1991**). This warming may result in shifts of climatic zones.

However the question is, whether the temperature variations could be explained by means of a single factor, namely the change of atmospheric CO_2 and other greenhose-gases (CH_4, N_2O, etc.). It is also well known, that the energy flux density of anthropogeneous sources in area as large as *100—1000* km^2 (megapolises, industrial centers) approaches the net solar radiation density, which is about *100* W/m^2 (Lockwood, 1986; Koppány, 1989). On the other hand many climatic stations are located in area with dense population. Thus at least a fraction of the global warming is apparent, and is consequence of urbanization.

It is also noteworthy, that the global mean temperature decreased by cca *0·3* K from *1940* to *1979*, while the cooling in this period in northern hemisphere was as much as *0·5* K. This fact suggests, that the atmospheric temperature is influenced by other factors besides the greenhouse affect, since the atmospheric carbondioxide has grown after *1940* continuously.

Therefore it is reasonable to investigate temperature series of length more than *100* year in order to deside: whether significant warmings took place before *1880*, too, and if yes, then these preindustrial warmings were higher or lower, than those in *20*-th century. *19* climatic stations were selected possessing more or less continuous temperature series started early *19*-th century or further back. The records available from these stations are insufficient for calculation mean global or hemispheric temperature variations. Still the early instrumental measurements might provide some information on regional temperature changes occured in last *2* or *3* centuries, mainly from great part of Europe, and from eastern United States.

Data sources

The temperature records have been taken mostly from Bracknell data basis up to *1960* in form of magnetic tapes. Some additional series were obtained from C. D. Schönwiese, Goethe University of Frankfurt am Main, among others the records of Central England (Schönwiese, 1988), and the data of period *1961—70* from World Weather Records. The series of Budapest since *1780* are available in A. Réthly's work (Climate of Budapest, 1947), and in file of the Hungarian Meteorological Service. The list of climatic stations is presented in *Table 1*.

The majority of stations (*14*) is located between 46—56°N latitudes, i.e. in moderate zone, three stations are in subtropical zone, and two stations in subpolar zone, respectively. *16* stations have continuous temperature series, two stations have interrupted series (Charleston and Copenhagen), in these cases either only the continuous part was used or the short interruptions were completed by interpolation. The records of Prague from *1939* to *1950* were added to those obtained from Bracknell.

Table I Geographical positions and observation periods of climatic stations

Central England	52·8°N	2·5°W	1659—1987
De Bilt	52·6°N	5·1°E	1706—1970
Charleston (USA)	32·9°N	80·0°W	1741—1759 1823—1965
Edinburgh	55·9°N	3·2°W	1764—1970
Basel	47·6°N	7·6°E	1755—1970
Genf	46·2°N	6·2°E	1753—1970
Trondheim	63·4°N	10·4°E	1761—1969
Stockholm	59·4°N	18·0°E	1757—1970
Koppenhága	55·6°N	12·5°E	1768—1776 1782—1788 1798—1970
Greenwich	51·5°N	0·0°	1763—1970
Berlin	52·6°N	13·4°E	1769—1970
Párizs	48·8°N	2·5°E	1764—1970
Prága	50·1°N	14·4°E	1771—1989
New Haven (USA)	41·3°N	72·9°W	1781—1970
Hohenpeissenberg	47·8°N	11·0°E	1781—1970
Bécs	48·3°N	16·4°E	1775—1970
Budapest	47·5°N	19·0°E	1780—1970
Kremsmünster	48·1°N	14·1°E	1796—1985
Genova	44·5°N	3·5°E	1833—1986

Method and results

As a first step decadal mean temperatures were calculated for all available climatic stations. By analyzing such rough materials sinchronous warmings or coolings appeard in some stations, e.g. the decade of **1731—40** proved warm both in Central England and De Bilt with positive decadal temperature anomaly (+*0·4* °C). Similar relative **warming** occured in **1791—1800** at twelf stations, in **1861—70** at eleven stations etc. On the other hand relatively great **negative anomalies** were found in **1811—20** at eight stations, in **1881—90** at 13 climatic stations etc.

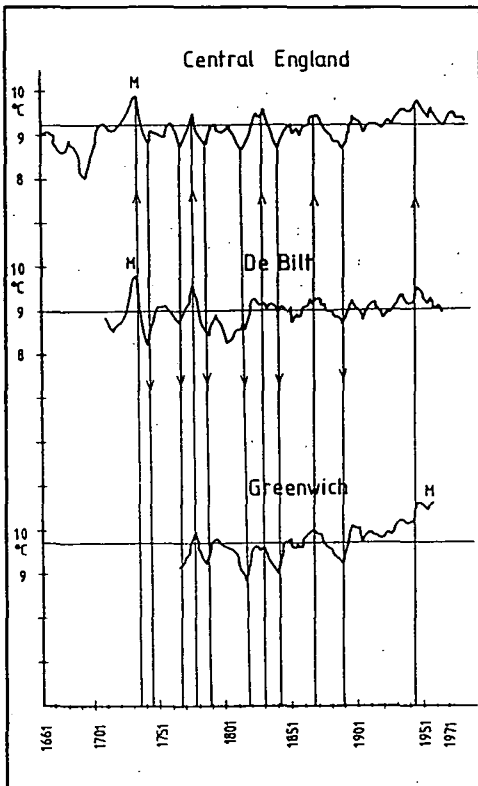

Figure 1 *Running 9-year mean temperature since the beginning of instrumental observations at Central England, De Bilt, Greenwich*

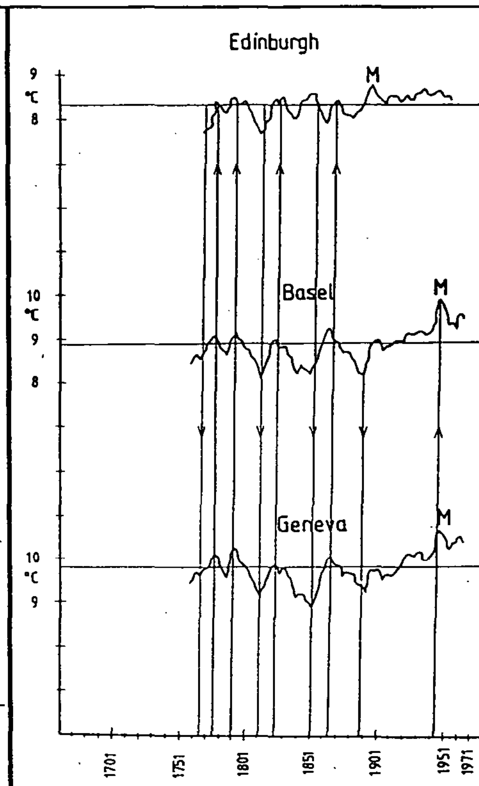

Figure 2 *The same for Edinburgh, Basel, Geneva*

In order to get more exact dates of local warming and cooling at various stations running *9*-year averages were determined. Further on the standard devitions of *9*-year mean temperatures and the mean values of the whole series were also calculated for each station. The secular temperature variations are presented in *Fig. 1—6.* The arrows directing upwards denote warming, „M" marks the maximum value in whole series of a given station, the arrows directing downwards denote cooling. One can recognize **sinchronous maxima** in some stations in periods of *1772—79*, of *1790—94*, of *1822—30*, of *1859—65*, of *1893—97*, of *1930-s* and *1940-s*. On the other hand **minima** can be found in some stations in periods of *1767—70*, of *1812—16*, of *1836—41*, of *1888—91*, of *1903—05* and of *1960-s*.

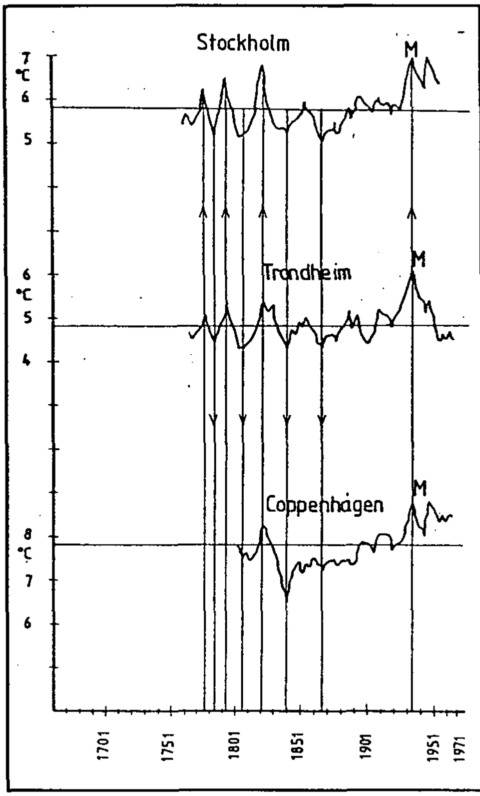

Figure 3 *The same for Stockholm, Trondheim, Copenhagen*

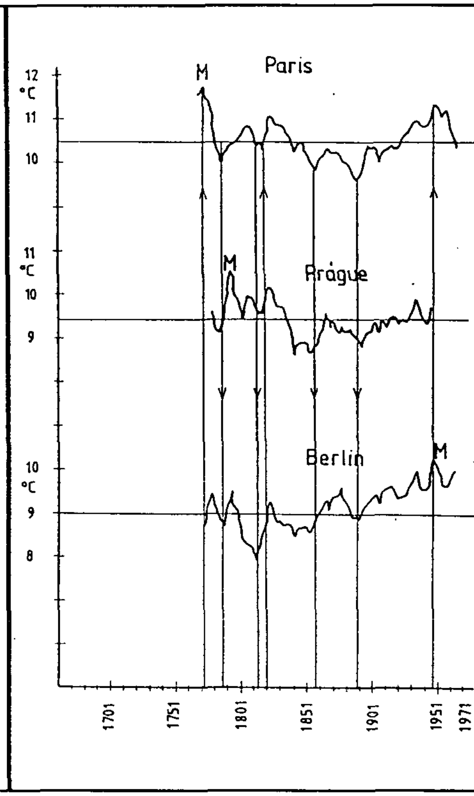

Figure 4 *The same for Paris, Prague, Berlin*

Schönwiese (1988) has found significant negative correlations between the mean temperature of northern hemisphere and several kinds of volcanic indices. In *Fig. 7* the spells of sinchronous warmings and coolings are presented during the period of *1731—1970* (above), while the dust vail index (DVI) is shown below since *1750*, with the names of greater volcanic eruptions. According to DVI there were calm volcanic periods in 1. *1770—80*, 2. *1790—1810*, 3. *1820—31*, 4. *1845—1880*, 5. *1913—1962*. These calm periods coincided with the years of temperature maxima mentioned above. Uncommonly long **volcanic silence** appeard between *1912* and *1963*, wich coincided with the significant warming in *20*-th century. **Strong volcanic activities** were registrated in the northern hemisphere: 1. around

1756 and 1785 (Laki, Iceland), respectively, 2. between **1815** and **1822** (Tambora), 3. in years **1875—83** (Krakatau), 4. around **1902** and **1912**, respectively (Sta Maria, Katmai), 5. and after **1963** (Agung). The coincidences of active volcanic spells with coolings in majority of climatic stations are evident in *Fig. 7*.

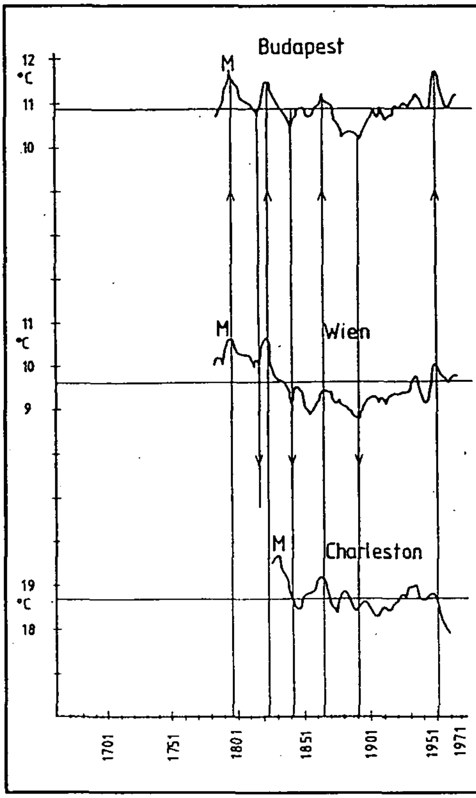

Figure 5 *The same for Budapest, Wien, Charleston*

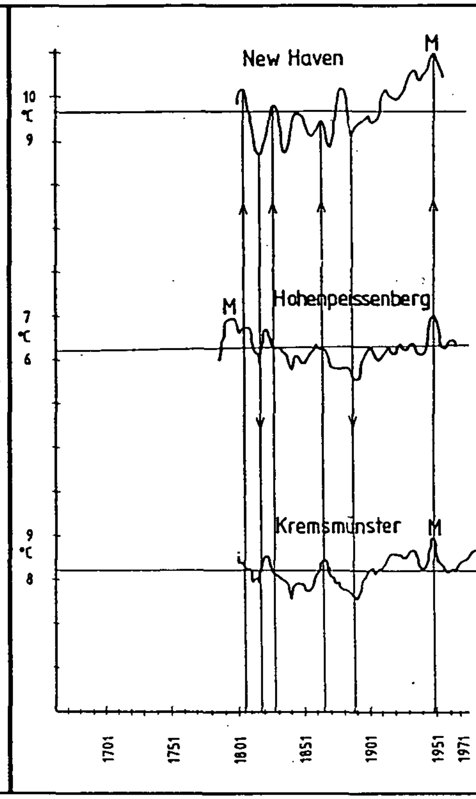

Figure 6 *The same for New Haven, Hohenpeissenberg, Kremsmünster*

One of the main purpose of this study is to investigate the temperature maxima before *1880* and to decide the evidence of warmer periods comparing with those in the *20*-th century. *Table II* contains the highest running *9*-year mean temperature anomalies at each stations, before and after *1880*. In the first column one can find the mean annual temperature for the whole series and the standard deviation of running *9*-year averages (s), respectively. In the second column the maxima years are shown with the annual temperature anomalies in form of ratio k = anomaly/standard deviation i.e. signal/noice, both concernd the warmings before *1880*.

Table II The warmest running 9-year mean temperature

Station	t°C	s°C	before	1880 (k)	after	1880 (k)	Δt°C
Basel	8·9	0·38	1794 1865	+0·87 +1·18	1947	+2·95	+0·67
Berlin	8·9	0·36	1794 1876	+1·44 +1·69	1947	+1·28	-0·5!
Budapest	10·9	0·33	1794	+2·52	1949	+2·45	-0·2!
Charleston	18·7	0·35	1831	+2·86	1935	+0.94	-0·7!
New Haven	9·7	0·59	1790	+1·57	1949	+2·19	+0·73
Central England	9·25	0·33	1734 1830	+2·36 +1·33	1947	+2·0	-0·12!
Coppenhagen	7·8	0·49	1822	+1·04	1947	+2·2	+0·57
De Bilt	9·0	0·30	1733 1777	+2·87 +2·03	1947	+2·1	-0·23!
Edinburgh	8·3	0·26	1794 1854	+0·65 +1·19	1936	+1·65	+0·12
Geneva	9·8	0·38	1794	+1·32	1947	+2·53	+0·46
Genova	15.7	0·36	1865	+2·50	1946	+1·67	-0·30!
Greenwich	9·7	0·39	1779	+0·69	1897 1947	+1·05 +2·38	+0·66
Hohenpeissenberg	6·2	0·33	1793—94	+2·39	1949	+2·45	+0.02
Kremsmünster	8·2	0·31	1800 1822 1863	+1·13	1947	+2·45	+0·41
Paris	10·5	0·46	1771—72	+2·67	1949	+1·76	-0·42!
Prague	9·5	0·52	1793	+2·11	1949	+1·35	-0·40!
Stockholm	5·8	0·48	1794 1822	+1·48 +2·08	1947	+2·67	+0·28
Trondheim	4·8	0·37	1794 1822	+1·43 +1·49	1934	+3·38	+0·7
Wien	9.6	0·50	1798	+2·18	1949	+1·04	-0·57!

The third column contains the same characteristics but after *1880*, while in fourth column Δt denotes the difference: maximum annual temperature in *20*-th century — maximum annual temperature before *1880*. If this difference is positive that means relative warming in the *20*-th century; if it is negative, then stronger warming took place in period before *1880*. The latter cases are marked with „!". Nine stations out of *19* have proved relative greater warming before *1880*, among others Charleston and Prague (*-0·67*°C), Paris (*-0·42*), Wien (*-0·57*), De Bilt (*-0·23*), Genoa (*-0·25*) etc.

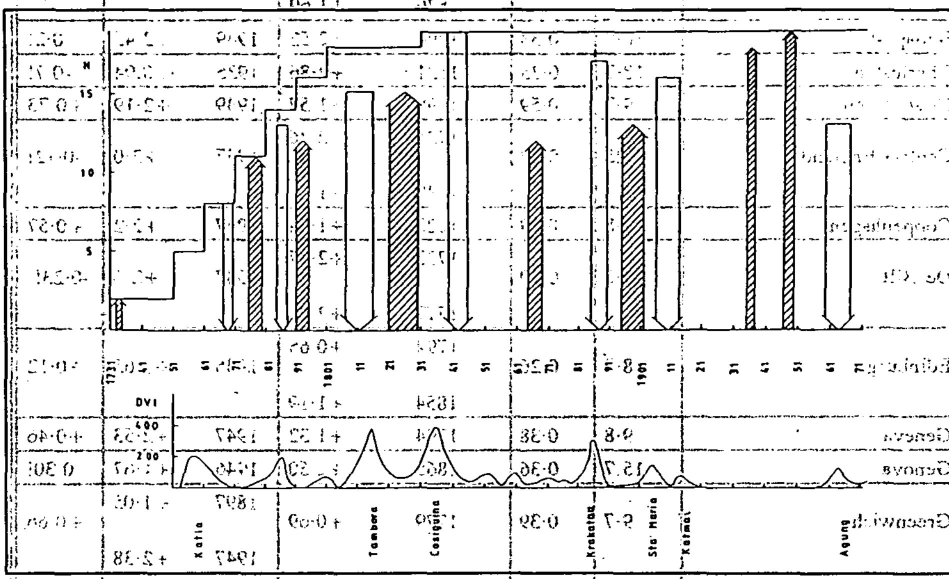

Figure 7. Above: Number of climatic stations (N) possessing temperature data after 1731; arrows upwards denote the number of stations with simultanous maxima, downwards denotes the number of stations with sinchronous minima. Below: Dust veil index with the names of significant volcanic eruptions

Hence it seems, that there took place significant warmings in *18*-th and *19*-th century, too, before increase of atmospheric carbon-dioxide due to industrialization. (Keil, 1961) analyzing long temperature series of Basel, Hohenpeissenburg, Jena and Prague, has got similar consequences even by using *30—40—50—60*-year smoothed temperature data.

After maxima in *1930-s* or *1940-s* universal cooling was observed by *1950-s* or *1960-s* in all stations (*Table III*). The ratio k = (change from maximum to minimum)/standard deviation exceeds unit at *16*, exceeds *2* at *7*, exceeds *3* at *2* stations.

Table III

	Highest running 9-year temp. in the 20-th century		The following minimum		Cooling after 1930-s or 1940-s	
Station	Year	°C	Year	°C	°C	k
Central England	1947	9·8	1966	9·2	-0·6	-1·91
De Bilt	1947	9·6	1966	8·9	-0·7	-2·37
Greenwich	1947	10·7	1954	10·5	-0·2	-0·51
Edinburgh	1936	8·8	1954	8·4	-0·4	-1·23
Basel	1947	10·0	1959	9·3	-0·7	-1·79
Genf	1947	10·7	1954	10·2	-0·5	-1·26
Stockholm	1947	7·1	1954	6·3	-0·8	-1·56
Trondheim	1934	6·1	1954	4·4	-1·7	-4·49
Coppenhagen	1947	8·9	1966	8·3	-0·6	-1·14
Paris	1949	11·3	1966	10·2	-1·1	-2·37
Prague	1949	10·2	1959	9·5	-0·7	-1·35
Berlin	1947	9·4	1958	8·7	-0·7	-1·89
Budapest	1949	11·7	1958	10·9	-0·8	-2·45
Wien	1949	10·1	1959	9·6	-0·5	-1·0
Charleston	1935	19·0	1959	17·9	-1·1	-3·26
New Haven	1949	11·0	1956	10·4	-0·6	-1·03
Hohenpeissenberg	1949	7·0	1966	6·1	-0·9	-2·82
Kremsmünster	1947	9·0	1959	8·1	-0·9	-2·74
Genova (1833—1982)	1946	16·3	1958	15·4	-0·9	-2·50

Conclusions

1. The temperature series longer than *100* year exhibit minima in period *1886—1891* in majority of climatic stations (see *Fig. 7*).

2. Numerous temperature maxima found before *1880*, and in *45%* of stations these maxima are higher, than those in *1930-s* or *1940-s*.

3. The warming in *1930-s* or *1940-s* coincides with longest calm volcanic period since *1750*.

4. A uniform cooling took place by *1950-s* or *1960-s*.

5. In light of these facts the global temperature variations may not be explained exclusively with greenhouse effect.

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Correlation Functions of the Global Sea-level Pressure Field

by L. MAKRA

J. A. University, Szeged, Egyetem u. 2. H—6722, Hungary

This study analyses if global sea level pressure fields are considered to be homogeneous and isotropic.

It is established that around any but given stations in choosen sectors of both hemispheres monthly mean sea level pressure fields — on the basis of sea level pressure isocorrelation curves — are not homogeneous and isotropic.

Of the representative stations of pressure centres pressure fields are in an increased degree not homogeneous and isotropic.

A globális tengerszinti légnyomási mező korrelációs függvényei. A dolgozat azt elemzi, hogy a globális tengerszinti légnyomási mező tekinthető-e homogén izotrópnak?

Az északi és déli féltekén választott szektorok tetszőlegesen rögzített állomásai körül a légnyomás izokorrelációs görbék alapján a havi közepes tengerszinti légnyomási mezők nem homogének és anizotrópok.

A légnyomási akciócentrumok reprezentatív állomásai körül pedig a légnyomási mező fokozottan ahomogén és anizotrop.

The correlation functions of the sea-level pressure field have already been studied by many, mainly in connection with the solution of optimal interpolational problems usual during the objective analysis of meteorological fields.

When studying the correlation functions and statistical structure of the sea-level pressure field, the homogeneity and isotropity of the fields studied are postulated for granted (e.g. **Gruza and Kaznaceeva, 1968**). In case of a fixed point M_0 and various points M, if the spatial correlation function between M_o and the points M does not depend on the coordinates of the point M_o, then the field is at the same time isotropic as well.

In this chapter, only spatial correlations are calculeted, temporal ones are not, for temporal correlatedness is covered to a certain degree, partly by coefficient time series obtained when decomposing sea-level pressure field to natural orthogonal components (**Makra, 1987**), partly by period analysis (**Makra, 1989**).

In order to find whether the sea-level pressure field can be considered a homogeneous isotropic, its monthly correlation functions have been examined. For that purpose, in the Northern Hemisphere in the regions of North America and Eurasia, as well as the oceanic basins, *4*, and in the Southern Hemisphere, *2* sectors have been separeted. The stations fixed sector by sector have been chosen optionally. These, with their serial numbers and coordinates, are the following: 60. Winly. These, with their serial numbers and coordinates, are the following: 60. Winnipeg, 49°54'N, 97°15'W; 65. D (a ship), 44°00'N, 41°00'W; 48. Kiev, 50°24'N, 30°27'E; 108. V (a ship), 34°00'N, 164°00'E; 201. Asuncion, 25°16'S, 57°38'W; 210. Alice Springs, 23°48'S, 133°53'E (*Fig 1*) (Makra, 1987). Around the stations (henceforth: poles) fixed, the decay of correlations are examined as far as the isocorrelation curves *0*.

On the basis of the correlation functions of the monthly mean sea level pressure fields (*Fig 2*), the following can be established: Mostly in the immediate neighbourhoods of the poles Kiev and Alice Springs, locally in almost every single monthly field (much more sparsely than in the ones of the others) can be found isotropic areas. In general, however, the isocorrelation curves notably stretch, that is level out, along the meridian — they are elliptic, as a consequence of the anisotropy of the individual monthly fields. From pole to pole and month to month, the decays of the isocorrelations are very different. Consequently, the individual monthly sea-level pressure fields are not homogeneous. Therefore, on the whole, the monthly mea ı sea-level pressure fields are not homogeneous and are anisotropic. The assumption of homogeneous isotropy can be regarded as a rather rough approach.

The isocorrelation curves associated with the individual poles, at the same time, demonstrate well — especially in the Northern Hemisphere, — the close connection of the winter Arctic high-pressure area with the sea-level pressure field over north America; in spring, with the decomposition of the polar anticyclone, the increasing zonality of the temperate-zone latitudes; as well as in autumn, the equalization of air pressure difference over the continental and oceanic surfaces.

It has been examined to what extent the above establishments are valid for the most characteristic ranges of the pressure field, the areas of pressure centres of action. The representative stations of the individual centres, with their map serial numbers and coordinates, are as follows: low-pressure station of Iceland — 23. Stykkisholm, 65°05'N, 22°46'W; Central Asian high pressure station — Irkutsk, 52°16'N, 104°19'E; Aleutic low-pressure station — 57. St. Paul, 57°09'N, 170°13'W; Azorean highpressure station — 92. Ponta Delgada, 37°45'N, 25°40'W; North Pacific high-pressure station — 109. Honolulu, 21°21'N, 157°56'W; South Pacific high-pressure station — 198. c (interpolated), 30°00'S, 100°00'W; South Atlantic high-pressure one -203. d (interpolated), 30°00'S, 10°00'W; Indian Ocean high pressure one — 208. e (interpolated), 30°00'S, 90°00'E (*Fig 1*) (Makra, 1987).

These stations having been fixed, it can, in general, be established that around them, the course of isocorrelation curves is even more deformed than in the preceding case. Thus, in the range of the action centres, the pressure field is ahomogeneous and anisotropic in an increased degree.

The influence area of the Iceland low-pressure centre is the greatest, which, in a considerable part of the year, extends over the whole Arctic zone, and all the year round, its connection is closest with the areas over Greenland and the Canadian archipelago. The high-pressure centre in Central Asia is well developed, with the exception of October, in the whole winter half-year (*Figs 3k, 1a, 1b, 1c*), and in the first three months of the year it extends to the Eastern Hemisphere's Arctic ranges (*Figs 3a, 3b, 3c*). The Azorian maximum has an effect, with exception of November, on a smaller area than the North Pacific. In the oceanic basins of the Northern Hemisphere, the barometric minimums have a much more strongly marked system of connections than their high-pressure equivalents have. Of the subtropical high-pressure action centres of the Southern Hemisphere, it seems that the South Pacific is the most developed and the stablest (*Fig 3*).

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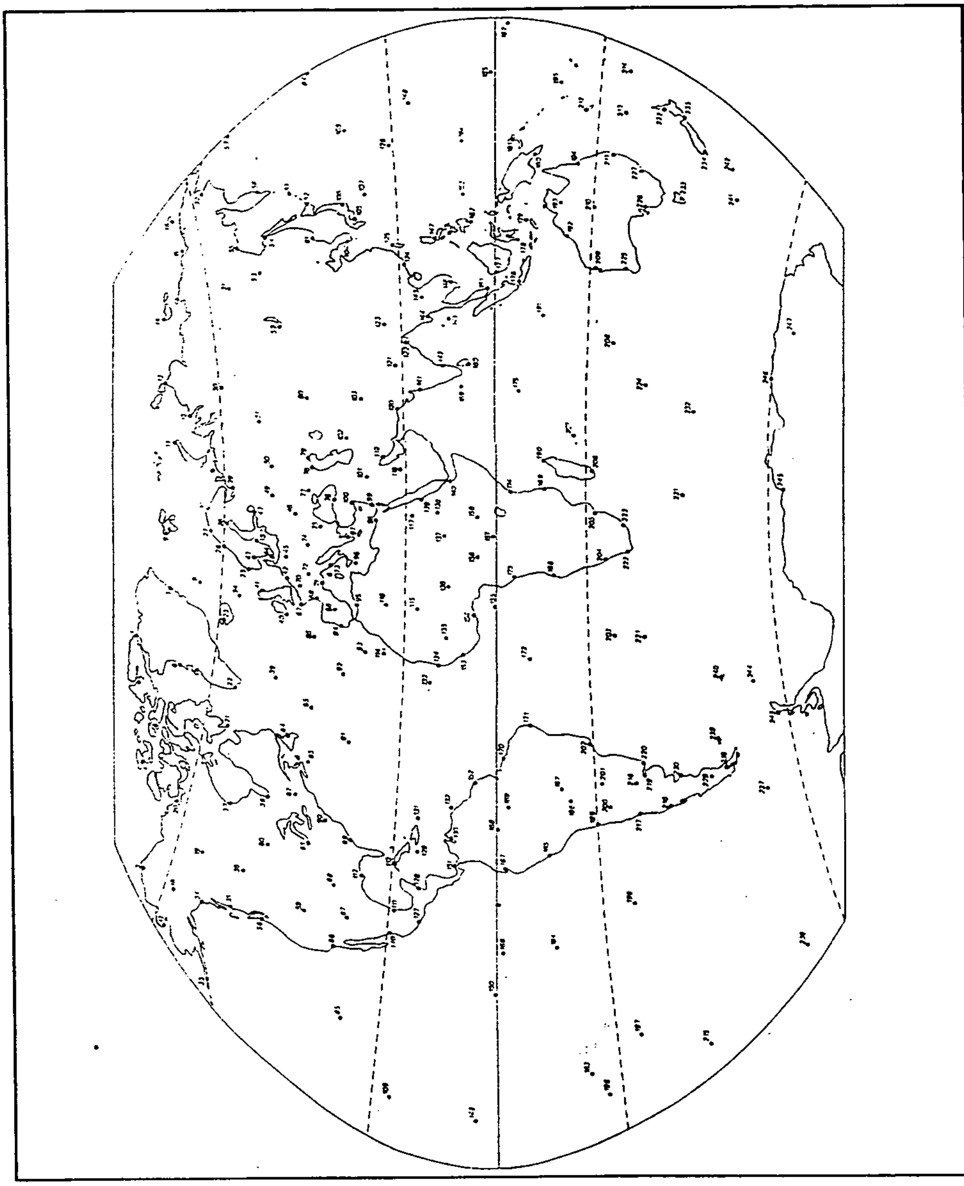

Figure 1 *Stations*

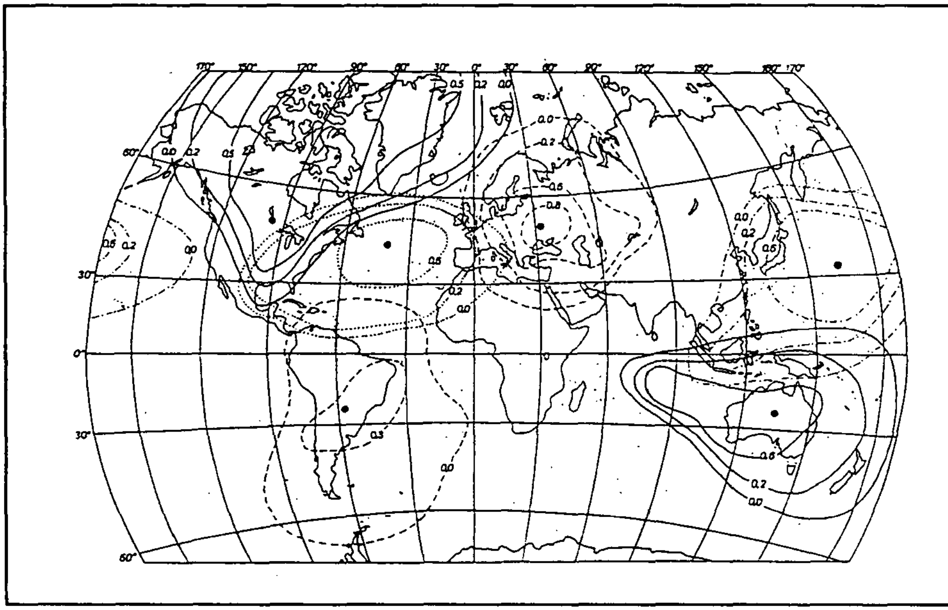

Fig. 2a. Correlation functions of sea-level pressure field, January

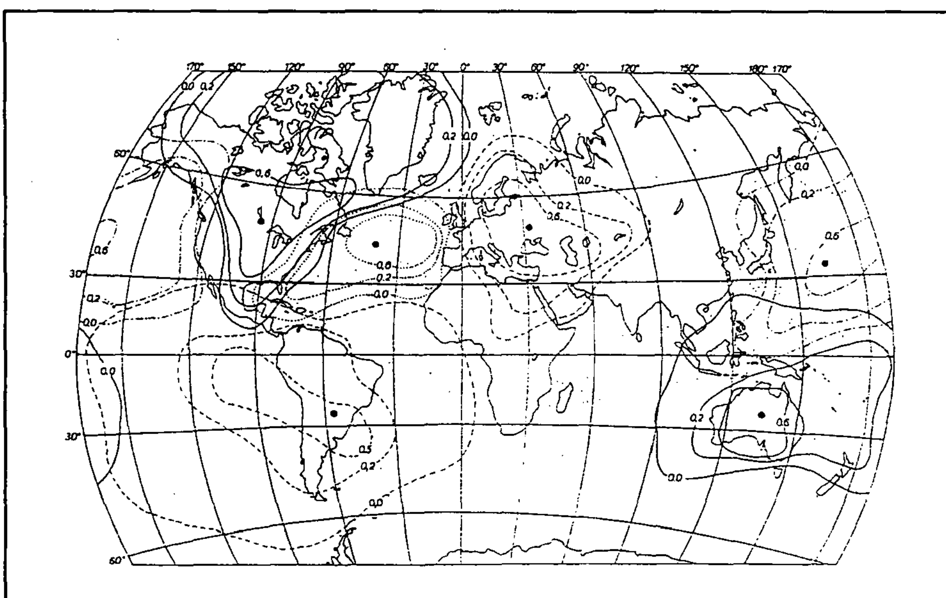

Fig. 2b. Correlation functions of sea-level pressure field, February

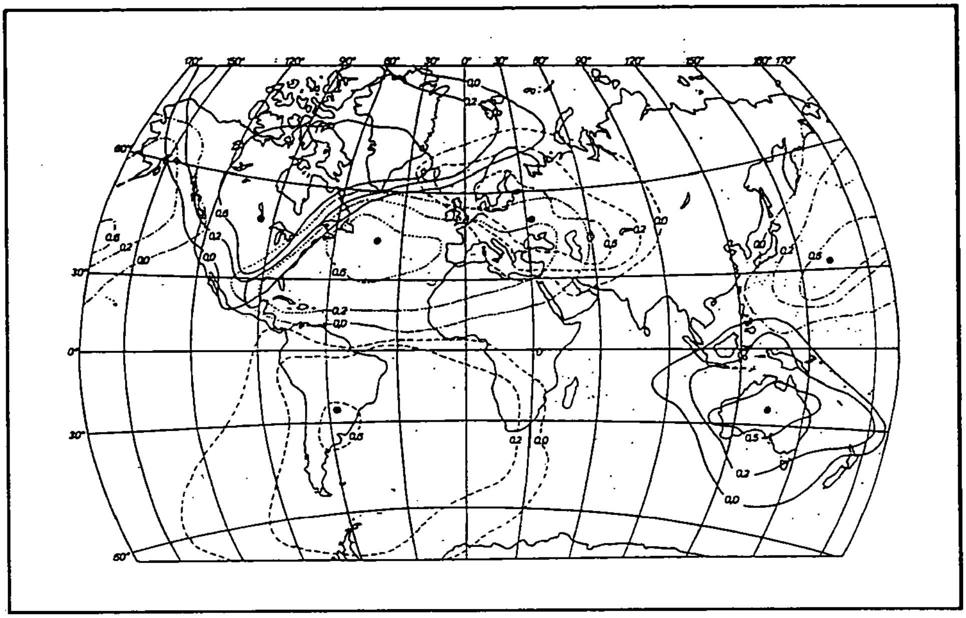

Fig. 2c. Correlation functions of sea-level pressure ,,eld, March

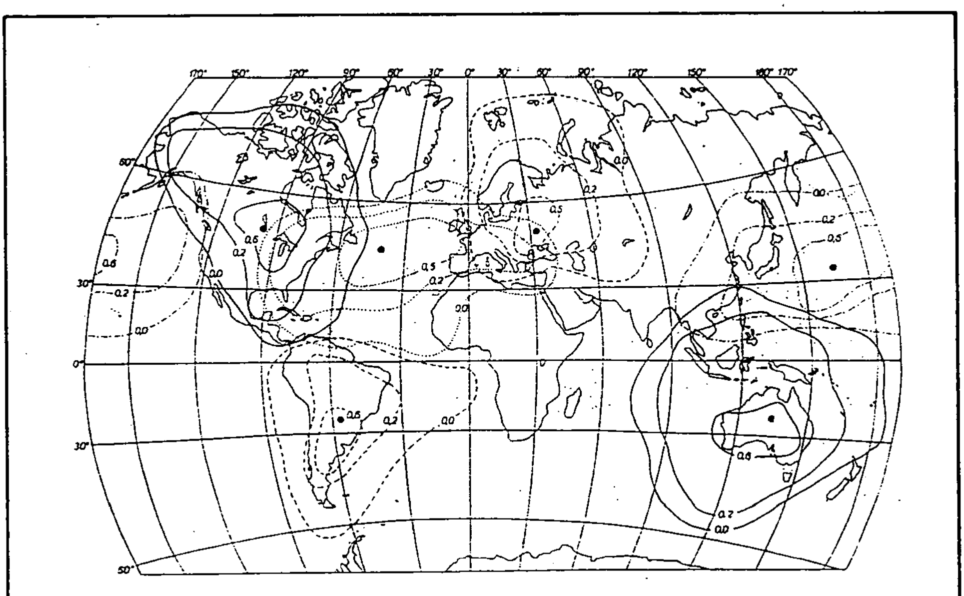

Fig. 2d. Correlation functions of sea-level pressure field, April

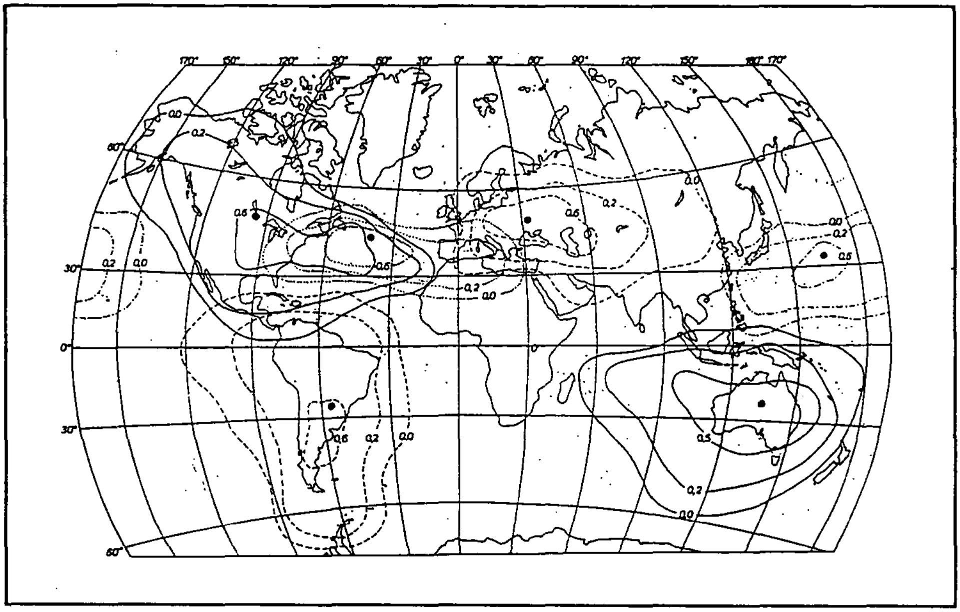

Fig. 2e. Correlation functions of sea-level pressure field, May

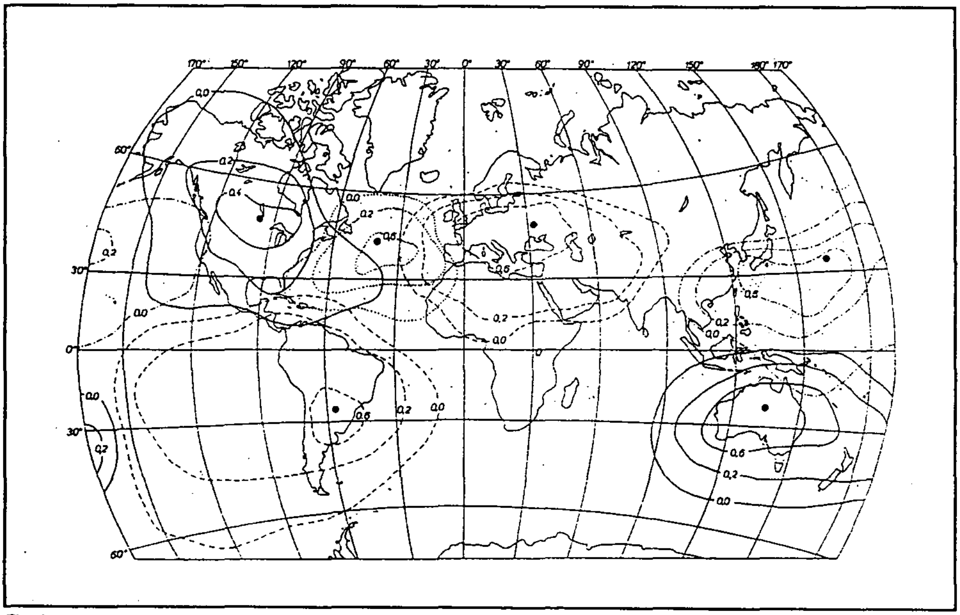

Fig. 2f. Correlation functions of sea-level pressure field, June

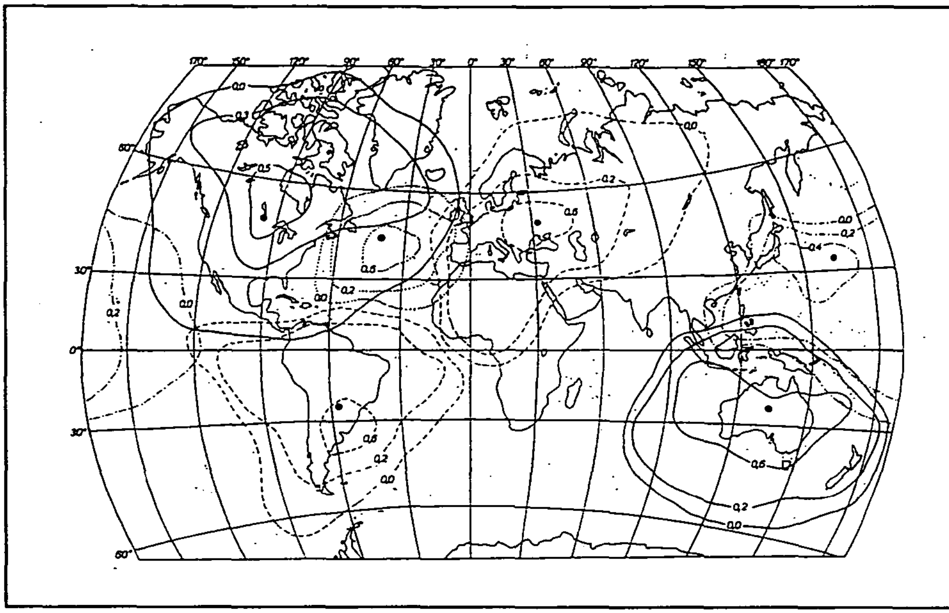

Fig. 2g. Correlation functions of sea-level pressure field, July

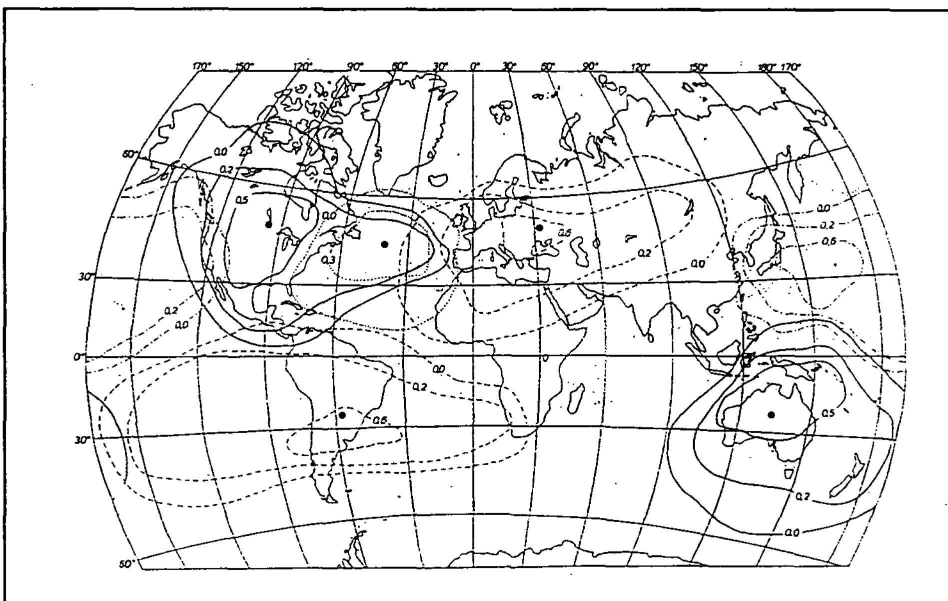

Fig. 2h. Correlation functions of sea-level pressure field, August

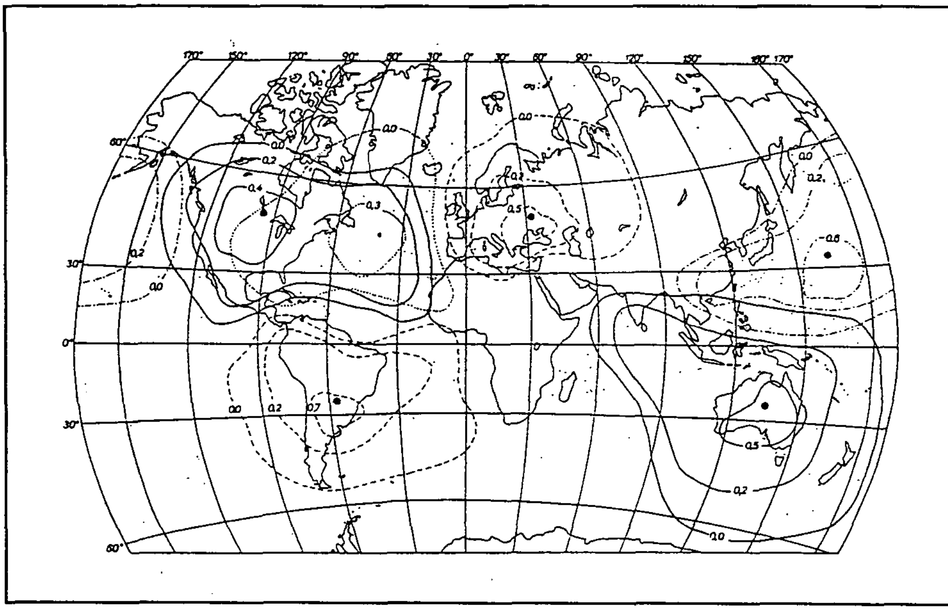

Fig. 2i. Correlation functions of sea-level pressure field, September

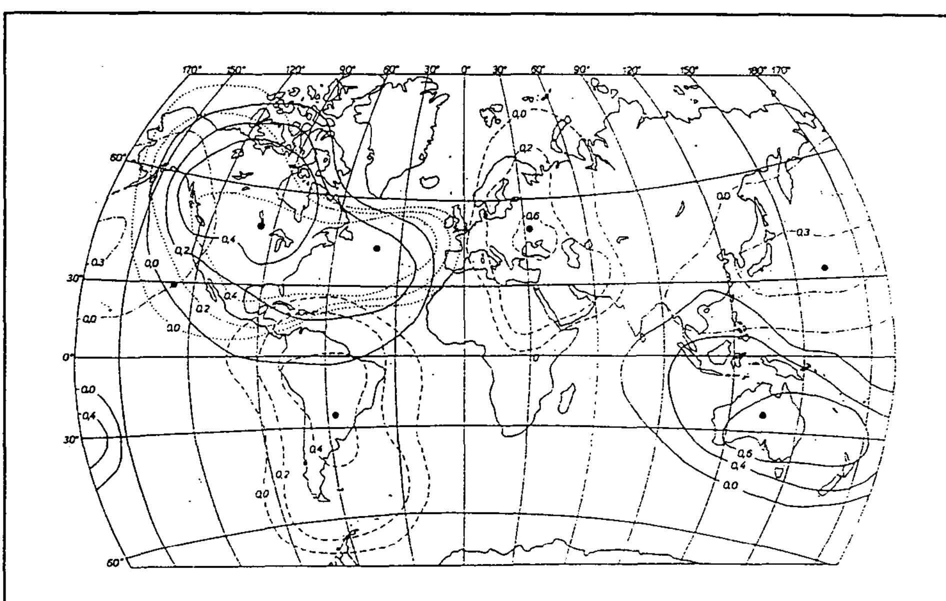

Fig. 2j. Correlation functions of sea-level pressure field, October

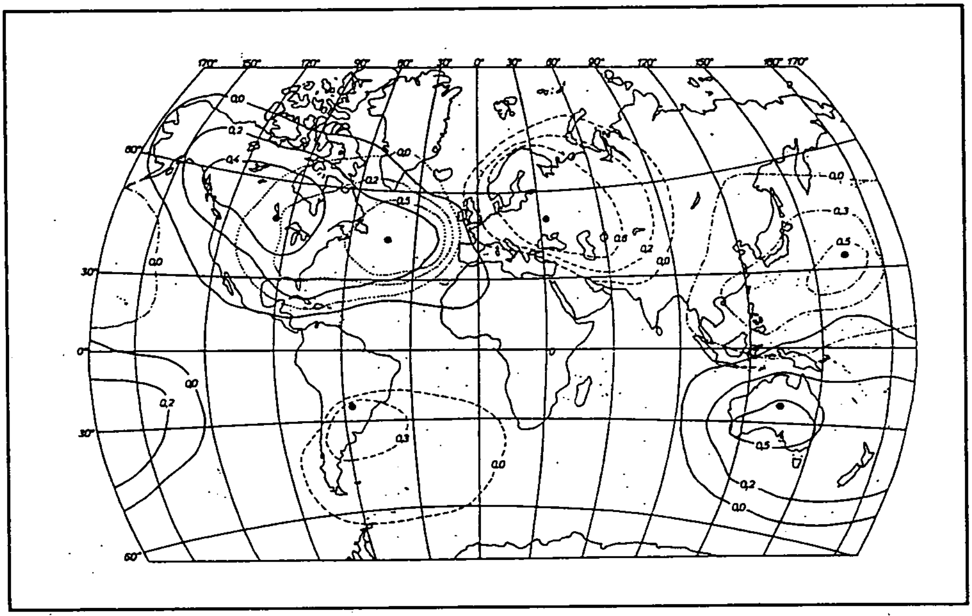

Fig. 2k. Correlation functions of sea-level pressure field, November

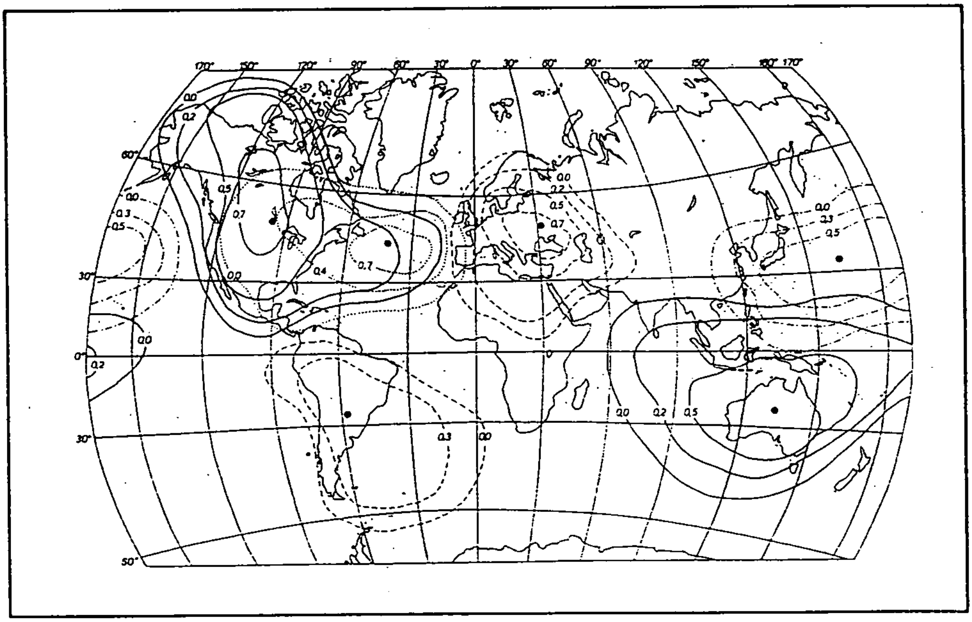

Fig. 2L Correlation functions of sea-level pressure field, December

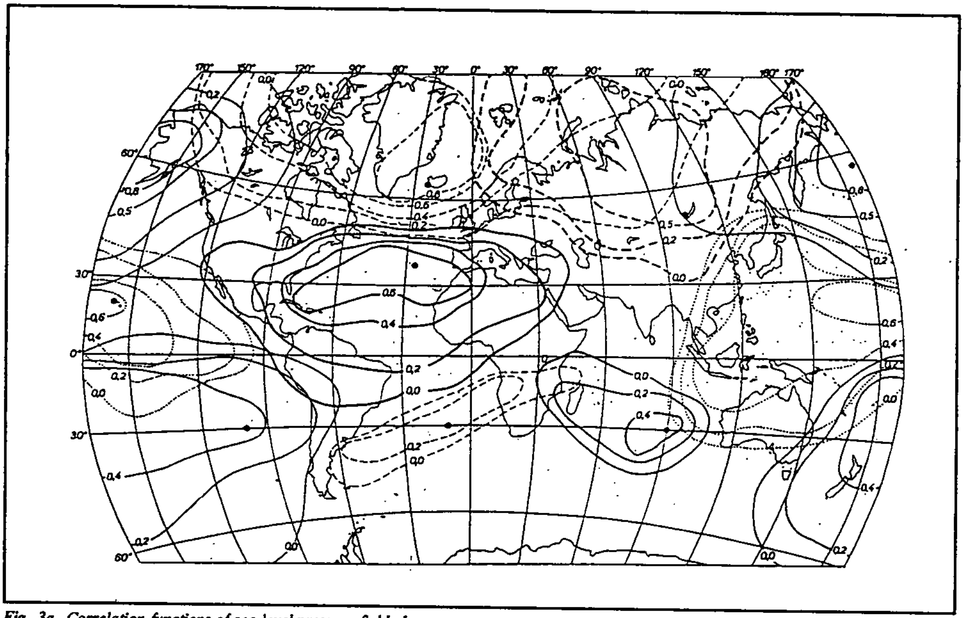

Fig. 3a. Correlation functions of sea-level pressure field, January

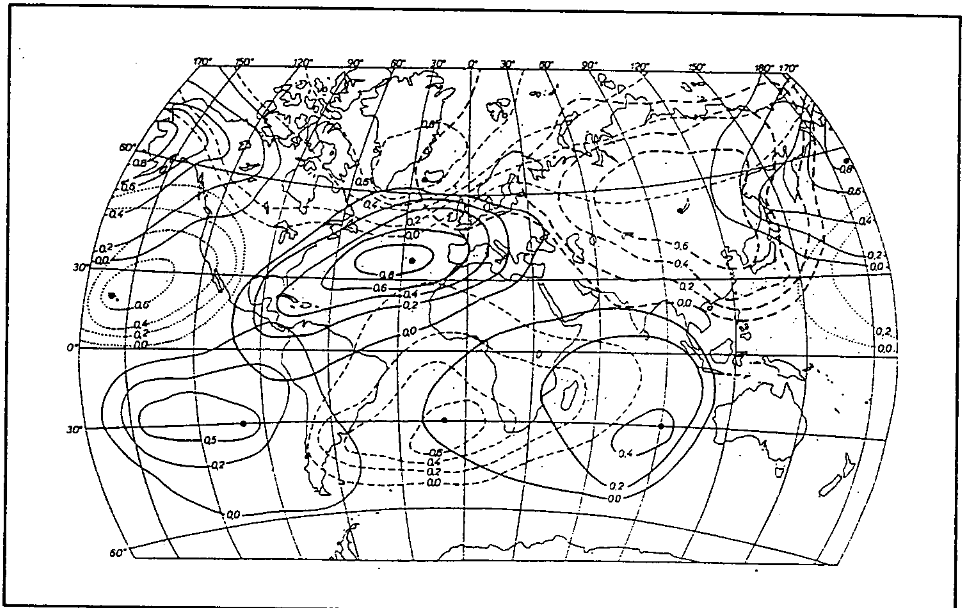

Fig. 3b. Correlation functions of sea-level pressure field, February

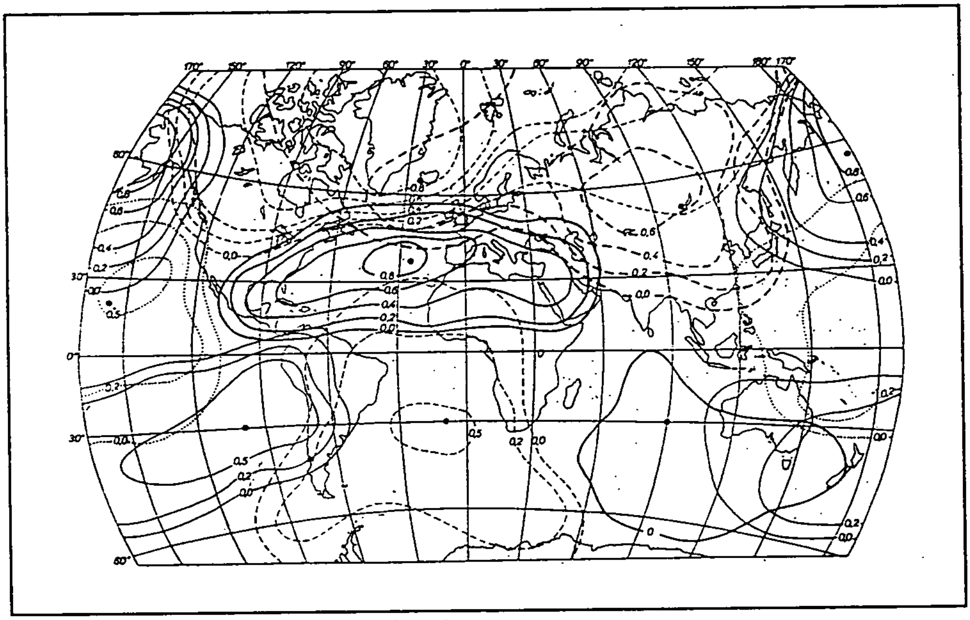

Fig. 3c. Correlation functions of sea-level pressure field, March

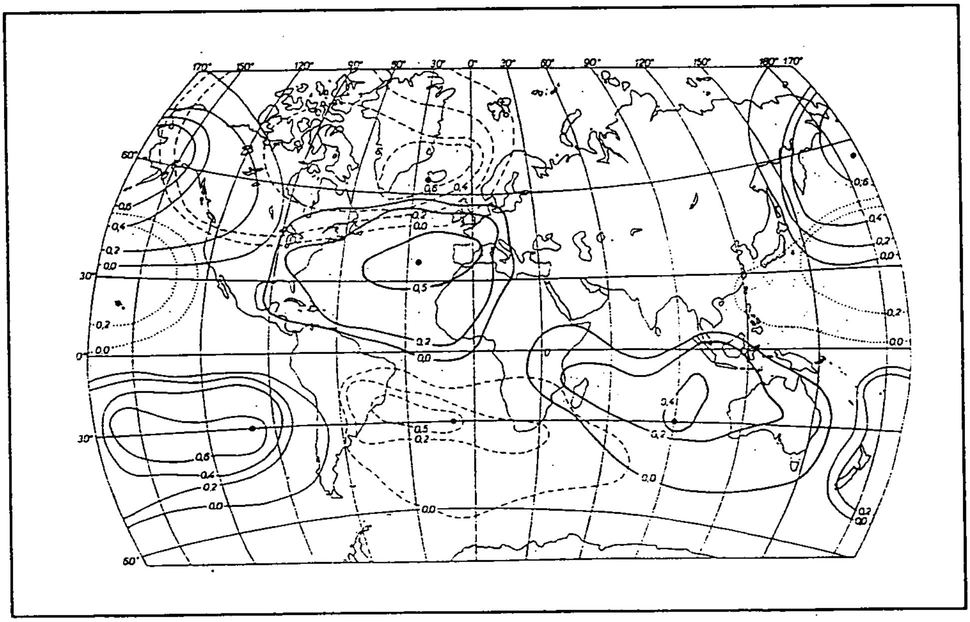

Fig. 3d. Correlation functions of sea-level pressure field, April

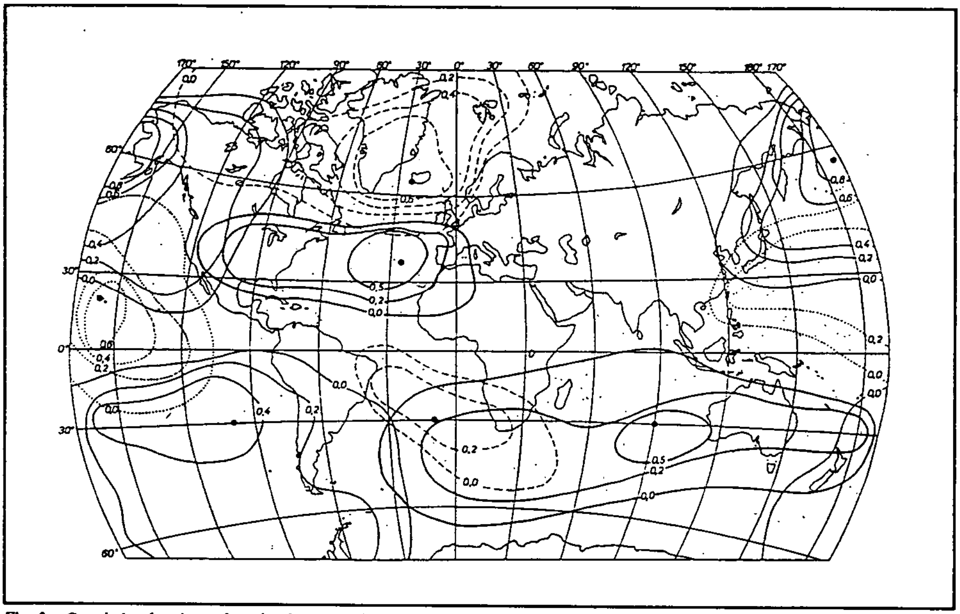

Fig. 3e. Correlation functions of sea-level pressure field, May

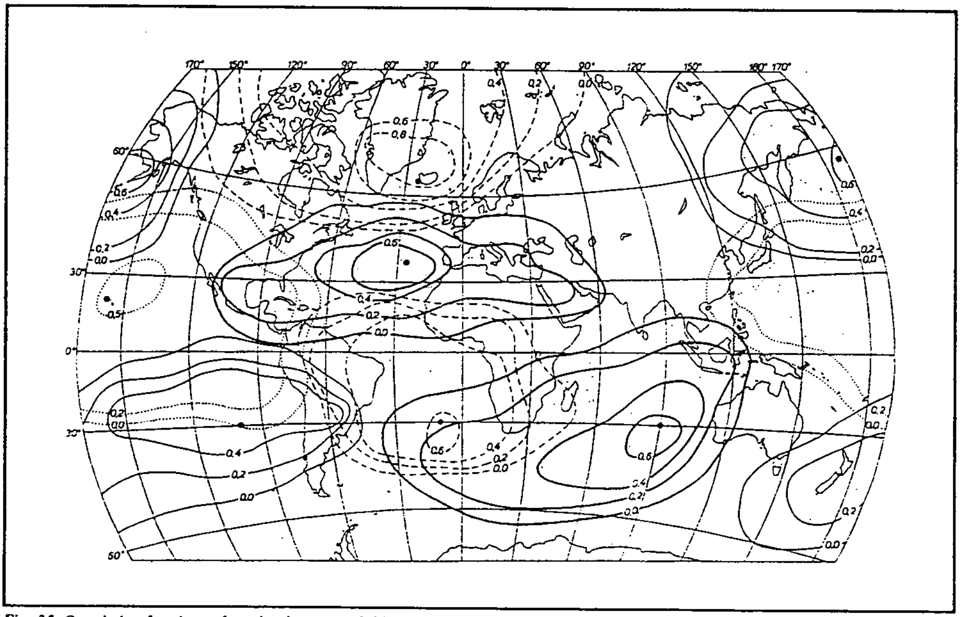

Fig. 3f. Correlation functions of sea-level pressure field, June

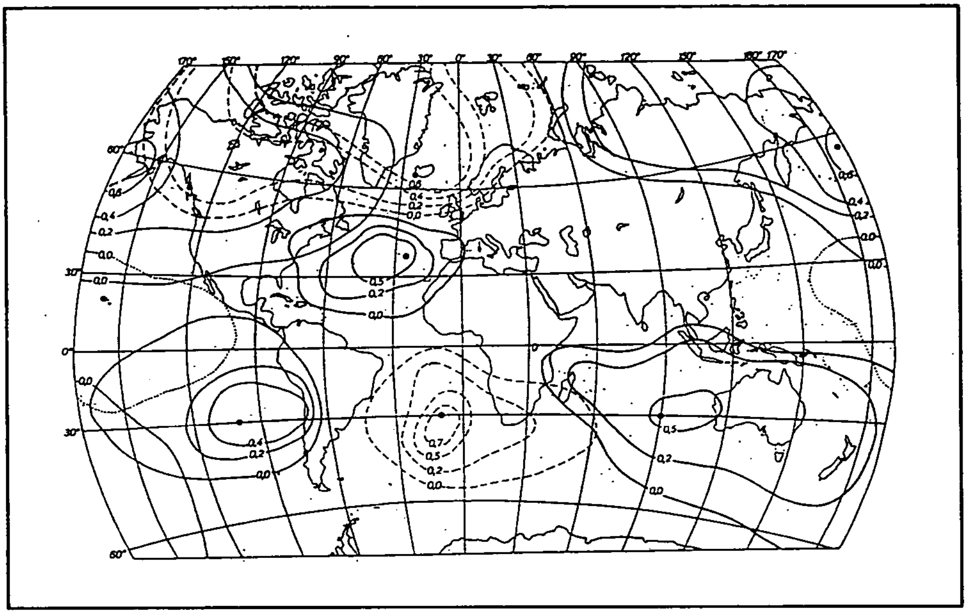

Fig. 3g. Correlation functions of sea-level pressure field, July

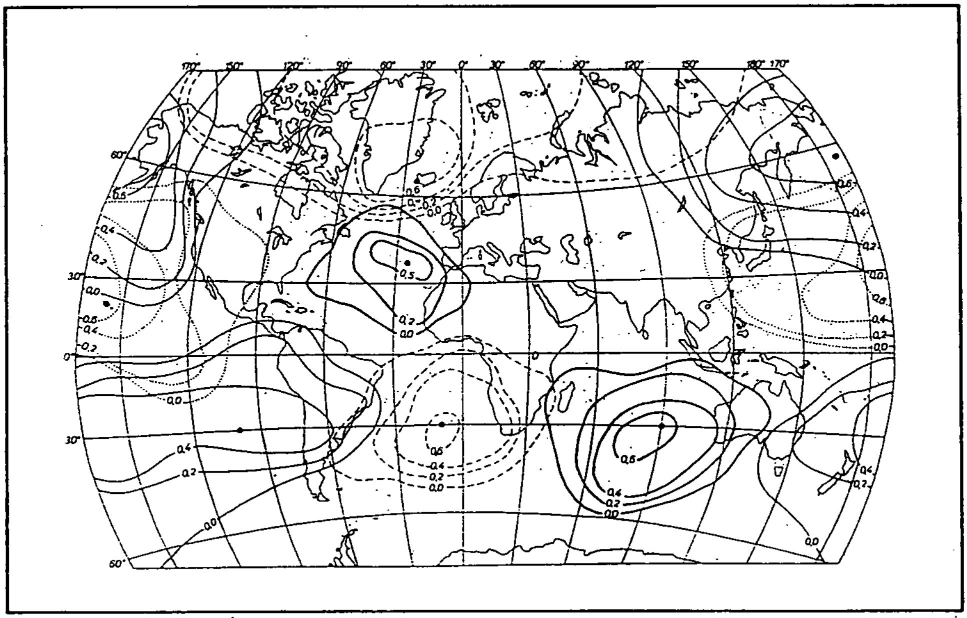

Fig. 3h. Correlation functions of sea-level pressure field, August

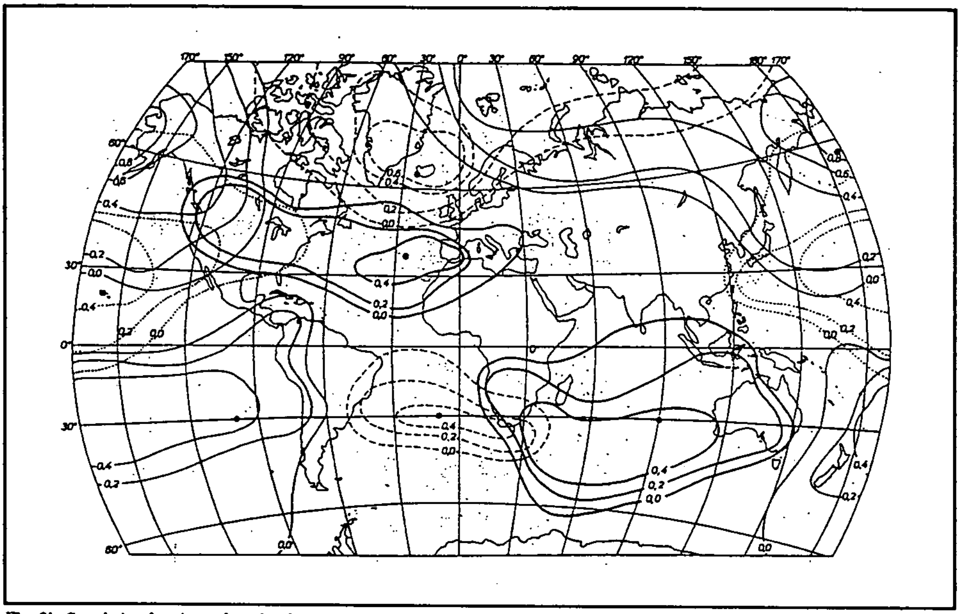

Fig. 3i. Correlation functions of sea-level pressure field, September

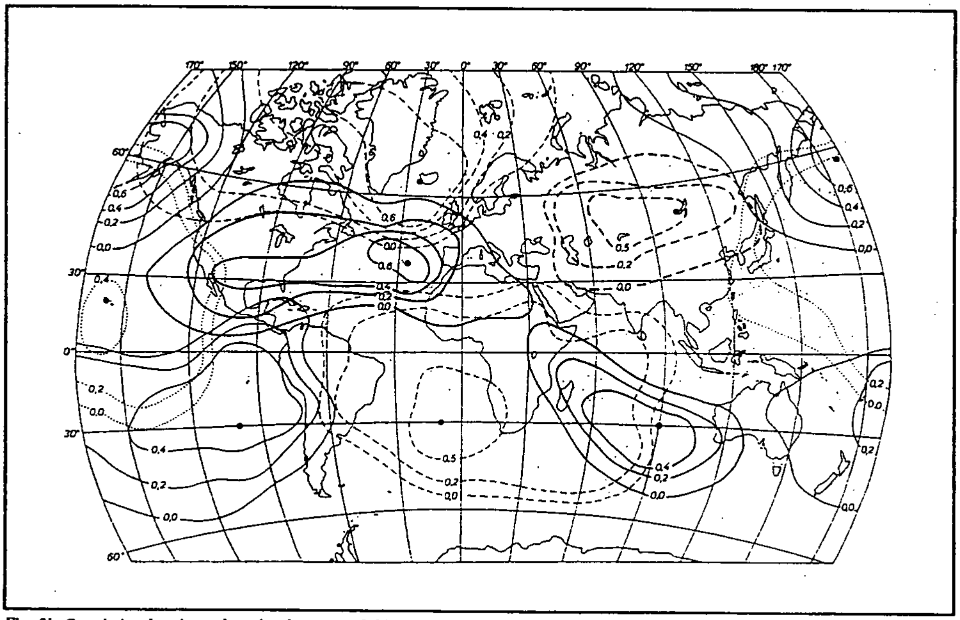

Fig. 3j. Correlation functions of sea-level pressure field, October

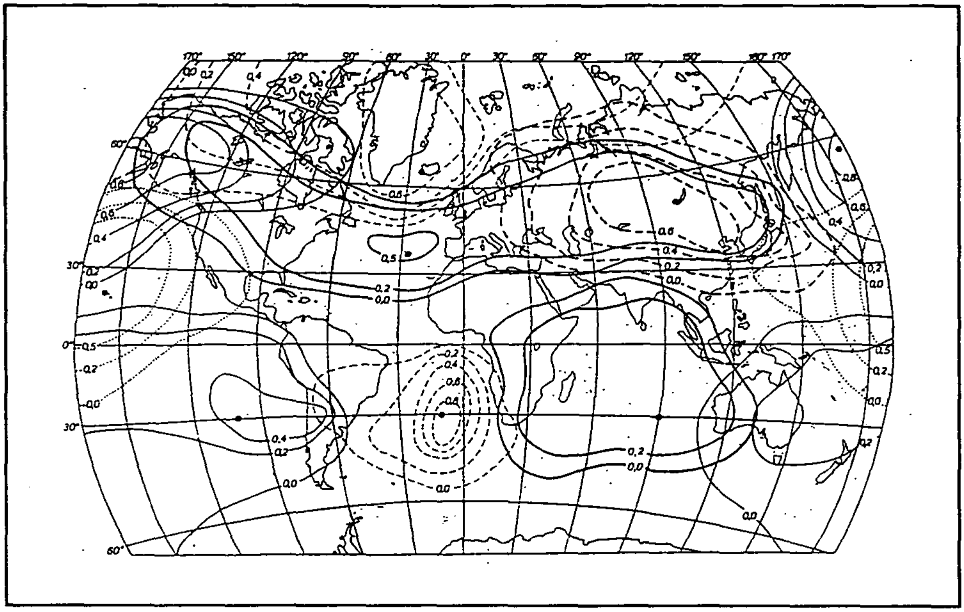

Fig. 3k. Correlation functions of sea-level pressure field, November

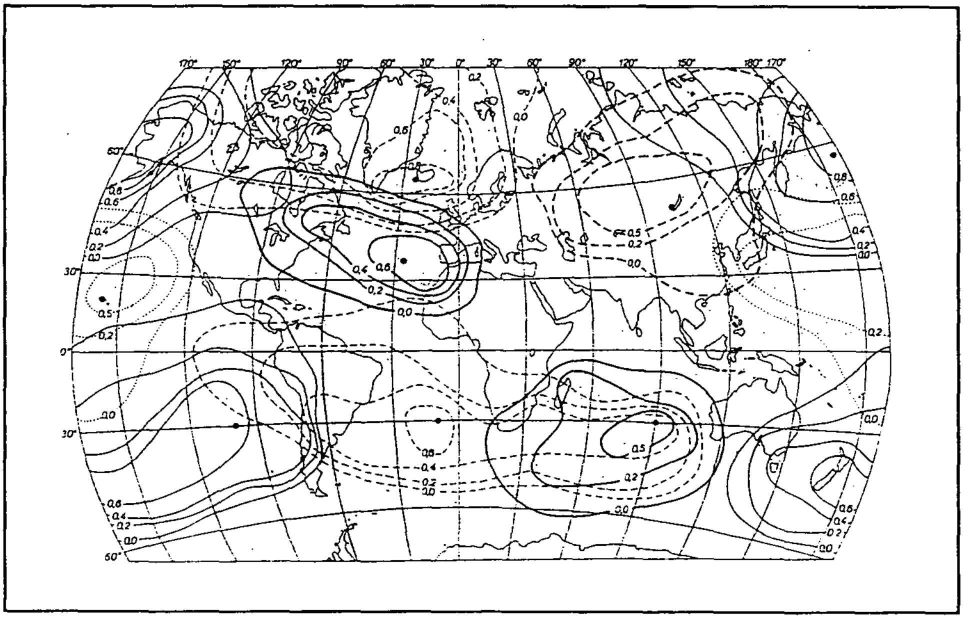

Fig. 3l. Correlation functions of sea-level pressure field, December

The Seasonal System of Urban Temperature Surplas in Szeged

by J. UNGER

J. A. University, Szeged, Egyetem u. 2. H—6722, Hungary

The data of city climate observations carried out at *11* stations in the area of the town of Szeged between *1977* and *1980* having been used, the degree and system of city temperature surplas has been investigated.

The investigations into pointing out the more marked characteristics of city climate have covered the sunny, advection-free days. By the help of the seasonal means counted from the daily mean temperatures of such days, the seasonal system of the appearing temperature excess has been compiled. Accordingly, the town centre is averagely *1·5—2·0*°C warmer than the surroundings of the town, but the urban—rural temperature difference may even exceed *2·5*°C.

A városi hőmérsékleti többlet évszakos rendszere Szegeden. Szeged város területén *11* állomáson *1977—80* között végzett városklímamérések adatait felhasználva vizsgáltuk a városi hőmérsékleti többlet mértékét és rendszerét.

Vizsgálataink a városklíma markánsabb jellegzetességeinek kimutatására a derült, advekciómentes napokra terjedtek ki. Az ilyen napok napi hőmérsékleti átlagából számolt évszakos középértékek segítségével megszerkesztettük a megjelenő hőmérsékleti többlet évszakos rendszerét. Eszerint a belváros átlagosan *1·5—2·0*°C-kal melegebb a város környezeténél, de a különbség a *2·5*°C-ot is meghaladhatja.

The bigger the town is, the more conspicuous the characteristics of urban climate are. The local features of temperature show themselves even in the cases of towns of medium order. Therefore, it is worth investigating the factors of city climate in Szeged also, though, in comparison to cities of the order of millions, their presence can only be demonstrated in a moderate form.

Szeged is found in the lowest-lying area of the Great Hungarian Plain, in the south—east of Hungary. Its geographical potentialities are explicitly advantageous from the point of view of the development of urban climate because the town and its sur-roundings are free from orographic effects. The number of its inhabitants is *178 000* (*7*).

Between *1977* and *1980*, under the direction of the Department of Climatology of József Attila University, observations covering several climatic components were going on at *11* points of the town, different from the view-point of building density. By partial using of the data obtained during these observations, several studies have been born (*2*), (*3*), (*6*), but a great deal of the data still lack processing. This lack is somewhat reduced by this study, the first part of the further, it is to be hoped, complete processing.

The Aerological Observatory at the airfield, as Station *1*, by virtue of its situation on the outskirts, represents the environment free of urban effect. About the situations of this and the other stations, as well as about the major morphological types of the building density of the town, information is given by *Fig. 1*.

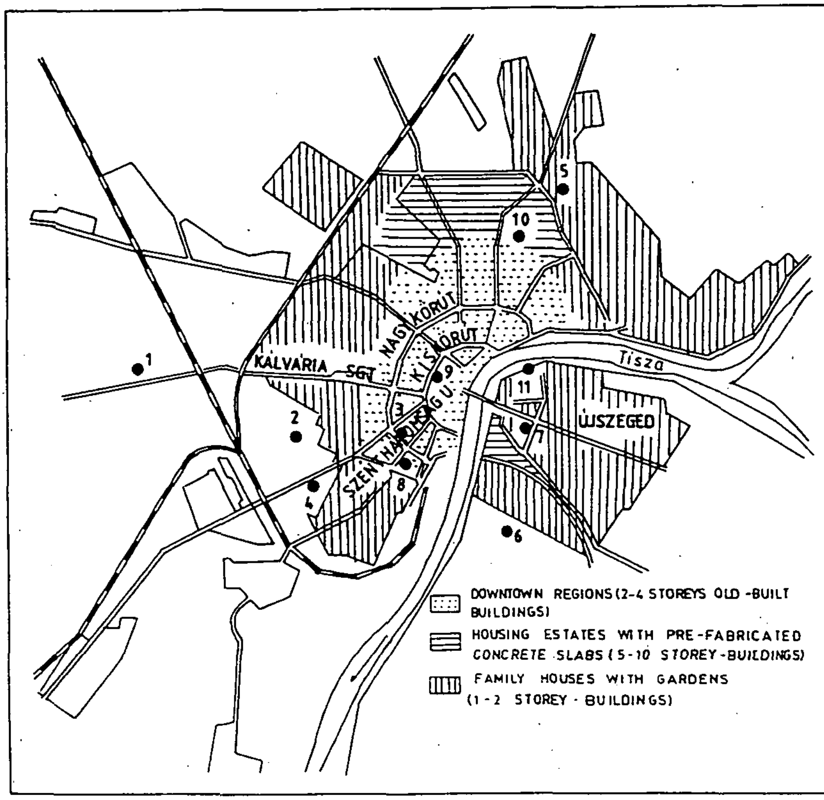

Fig. 1. The Szeged urban climate network: 1. Airfield, 2. 'Lakes Sancer', 3. 'Ady Square', 4. Agricultural Department, JGYTF, 5. Petöfi-telep (Petöfi Inhabitation), 6. Botanical Gardens, 7. Children's Hospital, 8. Bécsi körút ('Vienna Boulevard'), 9. Napsugár-bisztró ('Sunbeam Bistro'), 10. 'Water-Tower Square', 11. Lower Tisza Country Directorate for Water Matters

In the study the urban—rural temperature differences are investigated on the basis of daily temperature means, broken down according to seasons in the period between *1978* and *1980*.

On sunny, advection-free days, the characteristics of city climate as peculiar mesoclimate manifest themselves more strongly, while on cloudy, windy days, more weakly, or they completely disappear. According to the relation used in literature, in order to discontinue the difference of temperature between a city and its surroundings, a critical wind velocity

$$v = 3{\cdot}41\ lgP - 11{\cdot}6\ [m\ s^{-1}]$$

is needed averagely, where P means the number of the population of the residence. In this way, in the case of Szeged, the critical wind velocity happens to be $6{\cdot}2\ m\ s^{-1}$, (*1*), (2), (*4*).

In the light of the above, from the daily observing data of the 3 years examined, the days below an average cloudiness of *3* octas and an average wind velocity of $5\ m\ s^{-1}$ were filtered out. Further on, the temperature means of these days were, station by station, investigated. The advection-free and sunny days chosen are, by date, included in *Table I*.

Table I

Sunny days without advection between 1978 and 1980, as well as their percentages

1978		
January	1,2,3,5,6,10,14,15,19	(29%)
February	21,22	(7%)
March	3,4,13,23,28,29,30,31	(26%)
April	1,7,10,23,29	(17%)
May	31	(3%)
June	1,2,10,16,19,20,22,23,30	(30%)
July	1,4,5,9,13,14,16,17,18,20,23,24,26,27,28,29,31	(55%)
August	1,2,3,6,7,11,12,13,16,17,19,21,22,23,24,25,27	(55%)
September	4,14,15,16,21,26	(20%)
October	8,9,10,11,12,14,15,16,19,22,24,28	(39%)
November	—	(0%)
December	5,6,7	(10%)
1979		
January	3,5,7,8,13	(16%)
February	21,22,23,24,27	(18%)
March	2,3,4,7,9,15,20,25	(26%)
April	2,3,9,12,13,14,15,16,20,23,30	(37%)
May	10,15,16,18,19,20,21,25,29,30,31	(35%)
June	1,2,3,4,5,11,24,25,26,27,28,30	(40%)
July	6,11,16,19,20,24,25,26,29,30	(32%)
August	1,2,3,5,6,7,15,16,21,22,23,24,26,28,30,31	(52%)
September	1,2,3,6,7,8,12,13,14,17,19,20,21,25,30	(50%)
October	1,3,4,5,9,10,11,12,20,21,24,26,27	(42%)
November	23	(3%)
December	2,13	(6%)

. 1980

January	4,5,13,28	(12%)
February	20,21,27	(11%)
March	5,31	(6%)
April	12,13,14,15,16,17	(20%)
May	7,8,22,23,26,27	(19%)
June	2,12,13,14,15,20,21	(23%)
July	1,3,12,13,15,16,19,25,27,31	(32%)
August	1,3,5,6,7,8,10,16,17,18,19,26,27,28,30	(48%)
September	4,5,6,7,17,20,21,22,23,26	(33%)
October	4,7,17,21,23,29,31	(23%)
November	20,21,22,23,24,25,26	(23%)
December	13,19,30	(10%)

On the basis of the data of *Table I* it is observable that the days with the required qualities mostly appear as groups of days succeeding one another. That can obviously be explained by the range of the station by station identical weather situations over several quite long periods.

The days, selected, are grouped according to seasons. With this we obtained the season-to-season relative frequencies of the cases examined (*Table II*).

Table II

Seasonal and annual distribution of the sunny days without advection

	winter	spring	summer	autumn	year
Numbers of the days investigated	270	276	276	273	1095
Numbers of the days chosen	36	58	113	71	278
Relative frequencies of the days chosen (%)	13·3	21·0	40·9	26·0	25·4

It is visible from the table that the weather situations causing quite considerable temperature differences between the city and its environment are the most frequent in summer (*40·9 %*). In autumn (*26·9%*) and spring (*21·0%*), however, they occur fewer times, while in winter (*13·3%*), again, they are quite rare. This is explicable mainly by the greater cloudiness of the winter months and less by the force of the wind, for, at such times, wind velocities are generally smaller than in the summer months.

Later on, on the basis of the observations at *0700*, *1300* and *1900* hours (CET) the daily mean temperatures of the *3* years' days, selected, and grouped season by season, were calculated, station by station. The averages of these three observations are taken because uniformly in the cases of all *11* stations, observations had happened only at these three times.

From the daily mean temperatures we calculated the seasonal mean temperatures. The values of these averages, concerning the individual points of observation, are compared to the, identically calculated, seasonal means of Station *1* out of the town (*Table III*).

Table III

Seasonal means of each station and their differences from the seasonal means of the Station 1

Station	Winter		Spring		Summer		Autumn	
	Season	Differ.	Season	Differ.	Season	Differ.	Season	Differ.
1.	-3·07	0	12·92	0	22·03	0	12·76	0
2.	-2·78	0·29	13·51	0·59	22·32	0·29	13·70	0·94
3.	-1·72	1·35	15·15	2·23	23·09	1·06	15·39	2·65
4.	-2·82	0·25	13·75	0·83	22·71	0·68	13·26	0·50
5.	-2·33	0·74	13·77	0·85	22·39	0·36	14·66	1·90
6.	-2·97	0·10	13·09	0·17	21·85	-0·18	12·74	-0·02
7.	-2·02	1·05	13·50	0·58	22·80	0·77	14·15	1·39
8.	-2·07	1·00	—	—	22·93	0·90	14·16	1·40
9.	-0·69	2·38	14·62	1·70	23·76	1·73	15·46	2·70
10.	-1·42	1·65	14·14	1·22	22·93	0·90	14·49	1·43
11.	-2·52	0·55	13·72	0·80	23·79	1·76	14·04	1·28

The spring mean of Station *8* was disregarded because here in this period the series of observations were extraordinarily defective, so the mean, counted from few data, cannot be compared with the airfield value, counted up from the average of far more data.

By means of the difference values in *Table III*, the season-by-season system of the deviations of the daily mean temperatures from the corresponding values, representing the surroundings of the town, have been compiled. The isothermal charts of the anomalies are shown in *Figs. 2 to 5*.

It is visible in *Fig. 2* that in the winter months, in the centre and the closely built-up quarter lying north—west of it a little, there formed a mean temperature difference greater than *2·0*°C. The other parts of the centre, the quarters Tarján and Felsőváros ('Upper Town'), built up with big blocks, the vicinity of Nagykörút ('Great Boulevard'), as well as the Újszeged ('New Szeged') housing estate possess a considerable temperature excess *(1·0—2·0*°C).

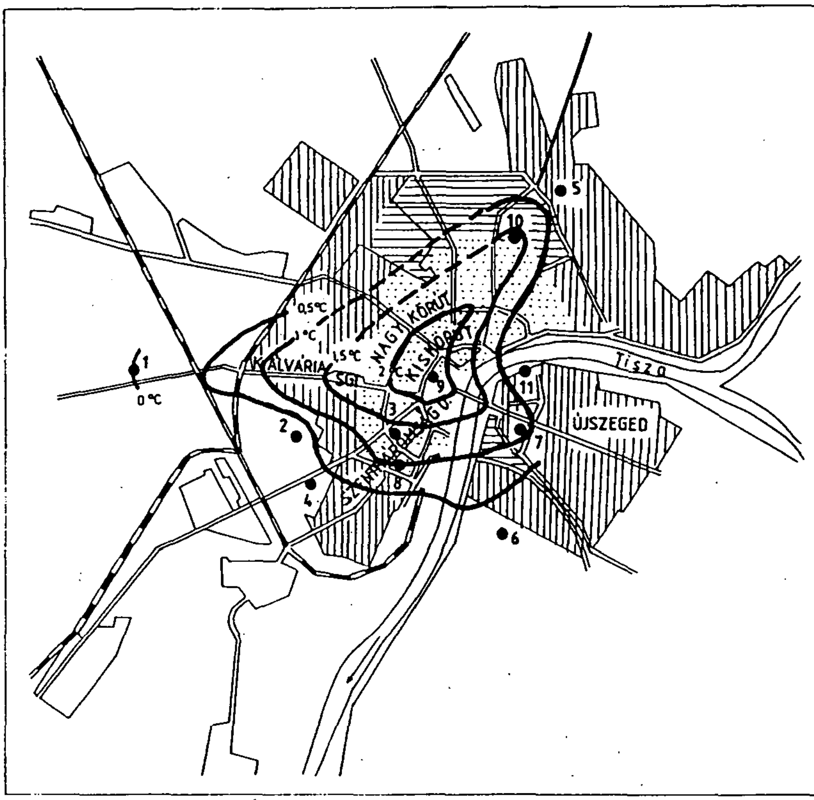

Fig. 2. The distribution of the winter mean daily temperature differences (1978—1980)

In the areas on the outskirts, mainly covered by houses with gardens, the difference is no longer very significant, it is as little as about *0·5*°C.

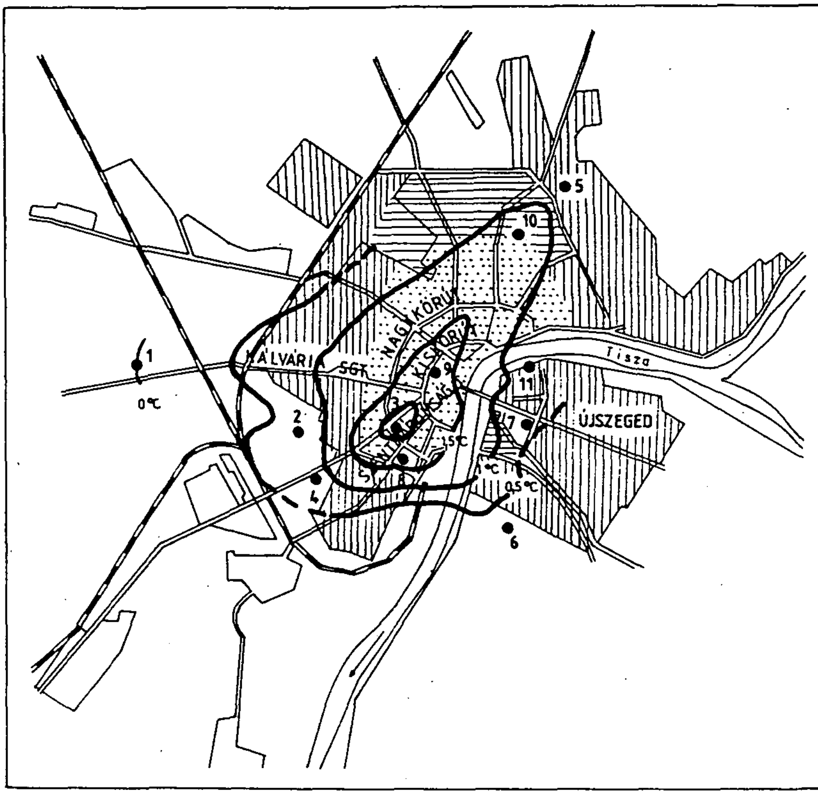

Fig. 3. The distribution of the spring mean daily temperature differences (1978—1980)

In the spring months (*Fig. 3*) the area possessing a major temperature difference (*2·0*°C) extends a little to the south—west, the area between Kálvária sugárút ('Calvary Avenue') and the beginning of Szentháromság utca ('Holy Trinity Street'). In addition, the difference is considerable (*1·5—2·0*°C) in all but the whole inner quarter, bordered by Nagykörút ('Great Bouleward'). Compared to the winter months, the extent of the area possessing a fairly great excess has reduced, which is explicable by the gradual ending of the heating season, and by the cessation of the heat radiation of household and communal heatings.

On the investigated days of the summer (*Fig. 4*), the isothermal system, formerly closed, slackens a little, the deviations are less marked. A fairly considerable temperature excess, which, however, only somewhat transcends *1·5* °C, comes into being in the north of the town centre. In the areas on the fringe, the difference is entirely insignificant already, and what is more, the more wooded Botanical

Gardens (Station *6*) are even cooler a little than the surroundings of the Airfield, lying in an open area.

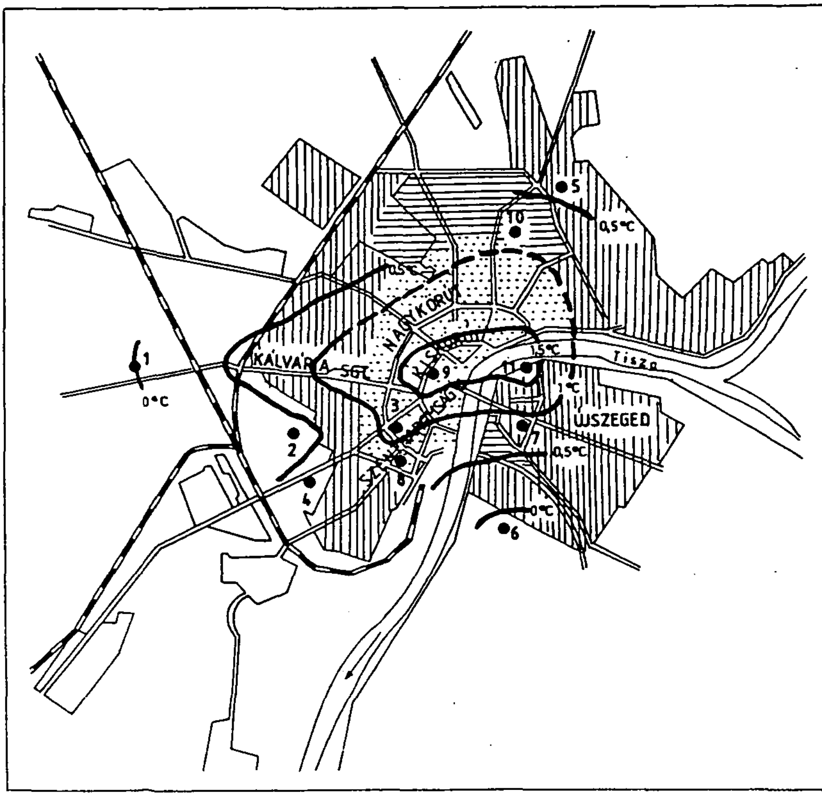

Fig. 4. The distribution of the summer mean daily temperature differences (1978—1980)

In the autumn months (*Fig. 5*), the temperature excess is considerable again (above 2·*0*°C) in all but the whole inner town, overlapping even Nagykörút ('Great Bouleward'). However, the northern part of the area between Kiskörút ('Little Bouleward') and Nagykörút, as well as the innermost and westernmost part of the Újszeged ('New Szeged') area already belong to the districts showing a lesser (*1*·*5*—*2*·*0*°C) temperature excess. The surroundings of the Botanical Gardens are not warmer in autumn than the Airfield either, while in Petőfi-telep ('Petőfi inhabitation'), an area showing a major deviation has formed. Compared to the summer period, the system of isotherms is much more closed, which refers to the more definite characters of the deviations.

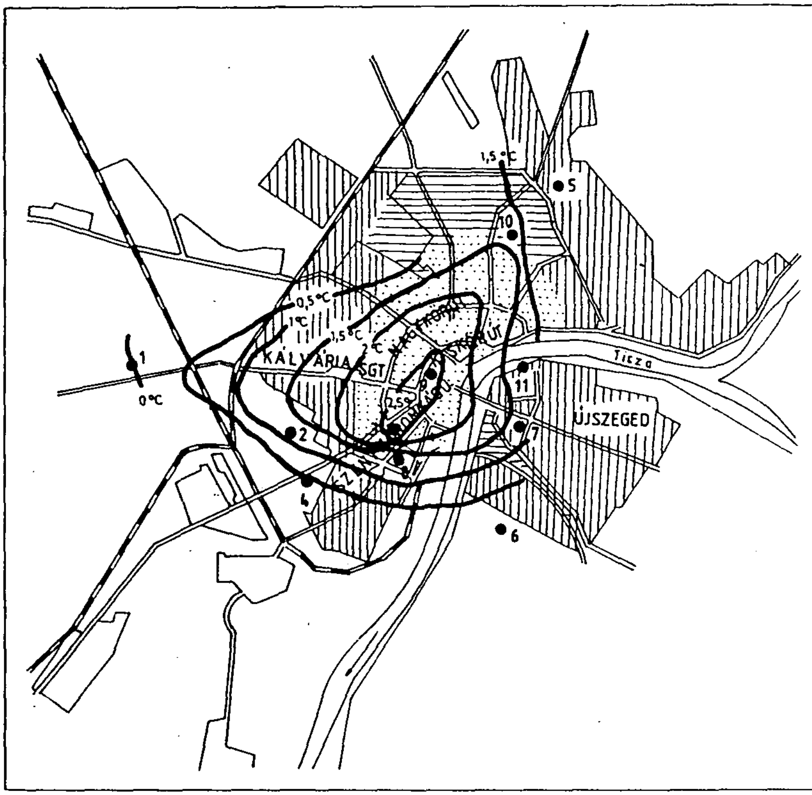

Fig. 5. The distribution of the autumn mean daily temperature differences (1978—1980)

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Mediterranean Climatic Character in the Annual March of Precipitation

by G. KOPPÁNY and J. UNGER

J. A. University, Szeged, Egyetem u. 2. H—6722, Hungary

The aim of the investigation is on the basis of the annual distribution of precipitation, and by suitable quantitative characteristics, distinguishing between the continental climatic type, characterizable by the summer maximum, and the Mediterranean one, characterizable by the winter maximum, in Hungary, Europe and the Mediterranean countries, respectively.

By the introduction of a suitable Mediterranean index (*MI*), as it is called, and by the calculation of this for several stations, we can obtain a survey of the regional distribution of the two kinds of climatic types.

Further on, we surveyed the *120*-year (*1870—1989*) precipitation series of Budapest and Szeged, and, according to the individual years, investigated the character of the *MI*. For the sake of exploring the possible periodic repetition, the Fourier analysis of the *120*-year *MI* series has been carried out.

Finally, we looked for a connection between the *MIs* of the two stations and the sea-level pressure anomalies of *17* European and Mediterranean stations. As a result we got that in Hungary, in case of an early summer well developed subtropical anticyclone, an autumn precipitation maximum is to be expected; while in case of a weak anticyclone, an early summer precipitation maximum.

Mediterrán klímajelleg a csapadék évi menetében. A vizsgálat célja az, hogy a csapadék évi eloszlása alapján megfelelő mennyiségi jellemzőkkel megkülönböztessük a nyári maximummal jellemezhető kontinentális és a téli maximummal jellemezhető mediterrán klímatípust Magyarországon, Európában, illetőleg a mediterrán országokban.

Egy megfelelő, úgynevezett Mediterrán index (*MI*) bevezetésével és ennek több állomásra való kiszámításával áttekintést nyerhetünk a kétféle klímatípus területi eloszlásáról.

A továbbiakban áttekintettük Budapest és Szeged *120* éves (*1870—1989*) csapadéksorát, és az egyes évek szerint megvizsgáltuk az *MI* jellegét. Az esetleges periodikus ismétlődés felderítése érdekében elvégeztük a 120 éves *MI*-sorok Fourier-analízisét.

Végül kapcsolatot kerestünk az állomások *MI*-ei és *17* európai illetve mediterrán állomás tengerszinti légnyomási anomáliái között. Eredményként azt kaptuk, hogy Magyarországon kora nyári erős szubtrópusi anticiklon esetén őszi csapadékmaximum, míg gyenge anticiklon esetén kora nyári csapadékmaximum várható.

On the basis of the annual march of precipitation, Europe is divisible into three climatic regions:

1. *Region of atlantic character*: with comparatively small annual fluctuation of precipitation, the wettest month mostly (in about *72%* of the stations) in the colder half-year (in the months October—March).

2. *Region of continental character*: with moderate annual fluctuation of precipitation, the rainiest month almost exclusively (in about *97%* of the stations) in the warmer half-year (in the months April—September).

3. *Region of mediterranean character*: with comparatively great annual fluctuation of precipitation, the rainiest month in the over-whelming majority of cases in the winter half-year.

In the course of the attempt made at parting these three climatic characters, we have used the means of many years of *123* European and, in part, Turkish climatological stations (**Koppány, 1989**). Considering the wettest month of the year, the continental and Mediterranean characters are well separable from each other; in the former, the maximum precipitation occurs in the summer half-year, in the latter, in the winter one.

The aim of the present investigation is that, on the basis of a suitable quantitative character number, we should distinguish the continental and Mediterranean climatic characters in Europe; furthermore, we should investigate how the two climatic effects vary in the precipitation series longer than 100 years of two climatological stations of Hungary. For it is obvious that in a transitional zone, such as Hungary, the two kinds of climatic characters alternate, depending on the fluctuation of circulation.

Method and Objective

In the course of the previous investigation mentioned, we found that in the majority of the climatological stations of Mediterranean character, the wettest month of the year is October or November; while in the part of the climatological stations of continental character which lie near the Mediterranean region, the rainiest month is May or June (**Koppány, 1989**). The precipitation march characteristic of the Mediterranean, as well as the transitional continental-Mediterranean climate are shown, respecting 6 climatological stations, by *Fig. 1*. The Mediterranean character presenting itself in the annual march of precipitation is distinctly visible at the stations Palma de Mallorca (Balearic Isles) and Milan, while the double maximum (May—June and October—November), at the transitional stations: Skopje, Pécs, Balatonfüred and Lillafüred. Further 6 climatological stations serve as models for the illustration of the Atlantic and continental characters, as well as of the continental-Mediterranean mixed character (*Fig. 2*). Whereas Brussels, Le Havre and London show an Atlantic-type precipitation march, Prague shows a typically continental-type one, Budapest and Szeged show a mixed-type one.

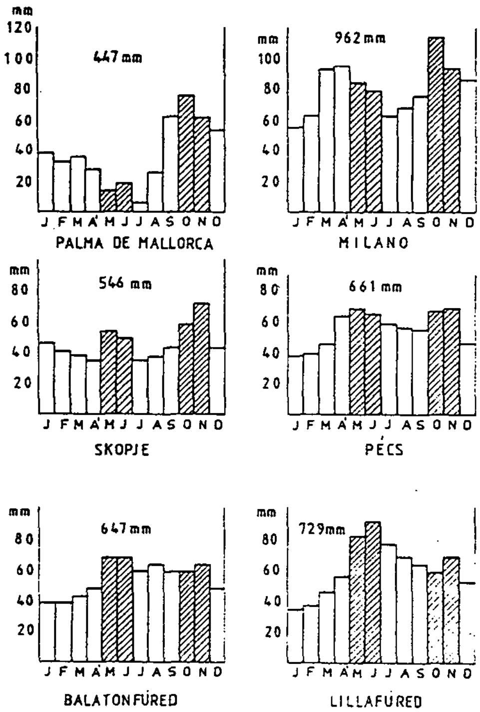

Fig. 1. Precipitation diagrams of the stations with mediterranean and transitional continental—mediterranean precipitation character

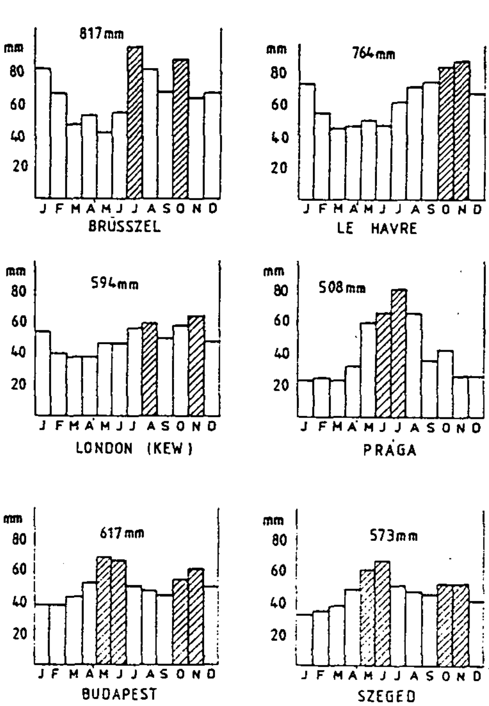

Fig. 2. Annual precipitation diagrams of the stations with atlantic, continental and continental—mediterranean precipitation character

For the quantitative characterizing of the Mediterranean character of precipitation we have brought in the following index:

$$MI = (P_{X\text{-}XI} - P_{V\text{-}VI})\cdot 100/P_{year}.$$

Here, MI is the Mediterranean precipitation index, $P_{X\text{-}XI}$ is the amount of precipitation of the months October + November in mm, $P_{V\text{-}VI}$ is the amount of precipitation of the months May + June in mm, P_{year} is the annual amount of precipitation in mm.

By calculating the MI for several climatological stations we obtain a survey of the regional distribution of the Mediterranean and continental climatic characters. The greater positive number we get in a given place for MI, the stronger there the Mediterranean character is, and vice versa: the greater negative value the MI has in some place, the stronger there the continental character of precipitation is. If somewhere the *MI* gives a value about zero, then there the Mediterranean and the continental effect are almost equal. Starting from this, we have determined the regional distribution of the *MI* for the part of Europe lying south of 50°N, as well as for Hungary.

As in certain parts of Hungary, the *MI* shows a slight continental character, we supposed that, regarding a long series of the years, the continental and Mediterranean effects present themselves alternately. Therefore we have investigated the precipitation series of two climatological stations which are in possession of at least *120* years' pluviometry, namely the data series of Budapest and Szeged between *1870* and *1989*. Questions laying claim to interest: 1. With what kind of relative frequency does the Mediterranean character occur over the years? 2. Is there a periodic repetition in the occurrence of the Mediterranean character? 3. Is there any connection between the *MI* and the anomalies of sea-level pressure?

Results

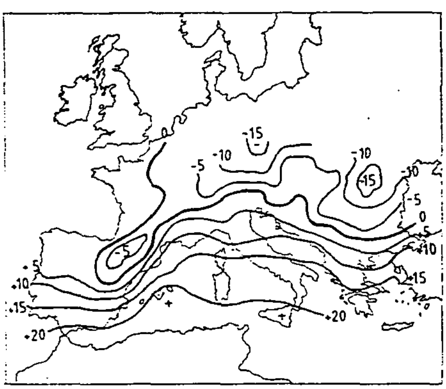

Fig. 3. Areal distribution of the Mediterranean index in Europe (1901–50)

The regional distribution of the Mediterranean index for the part of Europe south of 50°N has been determined by means of *49* (+*3*) stations (*Table I and II*), and is demonstrated in *Fig. 3*. It is visible from the figure that the line of zero value separating the areas of continental and Mediterranean character runs through the middle of the Balkan Peninsula, the south of Hungary, the Alps and the south of France as far as Spain, from where it turns with a sharp bend to the north. From this time onwards, however, it can no longer be considered as the dividing line mentioned, for in these Western European areas, the Atlantic climatic character holds true already.

Table I

The Mediterranean indices and the mean yearly amount of the precipitation of the stations of the network in Europe and about Europe (1901-50)

		MI	precip.			MI	precip.
1.	Porto	+2.17	1150	26.	Naples	+17.10	895
2.	Lisboa	+13.42	708	27.	Cagliari	+15.45	453
3.	Sevilla	+15.92	559	28.	Zürich	-7.66	1136
4.	Madrid	+6.65	436	29.	Genf	-0.12	852
5.	Zaragoza	-6.78	339	30.	Brussel	+6.97	817
6.	Barcelona	10.37	598	31.	London	+4.88	594
7.	Palma de M.	+22.60	447	32.	Prague	-15.74	508
8.	Valladolid	+1.66	362	33.	Salzburg	-11.10	1278
9.	La Coruna	+11.85	962	34.	Ljubjana	+4.14	1618
10.	Gibraltar	+21.60	815	35.	Zagreb	-0.46	864
11.	Marseilles	+13.74	546	36.	Belgrade	-7.88	701
12.	Ajaccio	+16.70	672	37.	Split	+8.33	816
13.	Bordeaux	+5.88	900	38.	Dubrovnik	+10.85	1272
14.	Toulouse	-6.07	659	39.	Skopje	+5.13	546
15.	Lyon	+0.37	813	40.	Sarajevo	+1.35	889
16.	Paris	-0.50	585	41.	Tirana	+12.44	1289
17.	Le Havre	+10.08	764	42.	Cluj	-16.64	613
18.	Brest	+1.60	1126	43.	Iasi	-11.40	518
19.	Tours	+1.74	689	44.	Bucharest	-10.23	440
20.	Nantes	+7.16	782	45.	Varna	-1.61	498
21.	Dijon	-1.22	739	46.	Sofia	-9.69	640
22.	Rome	+15.10	881	47.	Thessaloniki	+8.46	449
23.	Palermo	+22.02	772	48.	Athens	+16.95	405
24.	Milano	+4.57	962	49.	Istanbul	+13.80	679
25.	Florence	+8.30	795				

Table II

The Mediterranean indices and the mean yearly amount of the precipitation of the stations of the network in Hungary (1901-50)

		MI	precip.			MI	precip.
1.	Abádszalók	-4.18	502	19.	Pécs (Airfield)	+0.28	701
2.	Aggtelek	-7.22	622	20.	Szeged	-4.36	573
3.	Bácsalmás	-3.45	609	21.	Szentgotthárd	-5.87	817
4.	Baja	-2.84	599	22.	Szombathely	-3.28	700
5.	Balatonfüred	-2.47	647	23.	Villány	-1.15	697
6.	Békéscsaba	-5.15	563	24.	Zalaegerszeg	-4.16	745
7.	Cegléd	-4.04	545	25.	Lillafüred	-6.17	729
8.	Budapest	-3.40	617	26.	Győr	-3.14	541
9.	Debrecen	-4.27	585	27.	Komárom	-4.92	549
10.	Drávafok	-0.28	699	28.	Mosonmagyaróvár	-3.70	594
11.	Kaposvár	-3.28	715	29.	Kecskemét	-2.51	517
12.	Kőszeg	-5.52	779	30.	Pápa	-3.43	641
13.	Mohács	-1.44	624	31.	Sopron	-5.23	688
14.	Nagykanizsa	-2.32	777	32.	Székesfehérvár	-3.81	577
15.	Pécs (University)	+0.30	661	33.	Szolnok	-4.00	524
16.	Pécs (Mecsekalja)	+0.15	650	34.	Romhány	-2.20	585
17.	Misinatető	-0.14	723	35.	Kiskunfélegyháza	-2.46	540
18.	Pécs (T.T.College)	+0.29	683	36.	Orosháza	-4.31	533

South and north of the dividing line, the absolute value of the *MI* rapidly increases. In the southern, Mediterranean areas, a zonality parallel with the latitudes beautifully takes shape, with maximum *MI* values above *+20*. (Sicily, southern Spain.) In the northern, continental parts, the zonality is not so much definite, it is especially the Carpathian Basin that causes a big break in the run of the isobars. In the European parts investigated, the greatest negative *MI* values, those below *-15*, are found in Transylvania and Bohemia, two basin-type regions.

A more precise distribution of the *MI* in the territory of Hungary has been designed in *Fig. 4* by means of *36* stations (*Table II*). It can be seen that a (Mediterranean) area of a faintly positive value can only be disclosed in the surroundings of Pécs, while the rest of the country, without a more definite zonality, can be characterized by various, not very great negative values. (Continentality.) The regions with the largest negative *MI* values, those below *-5*, are found in the north-eastern, western and south-eastern parts of the country.

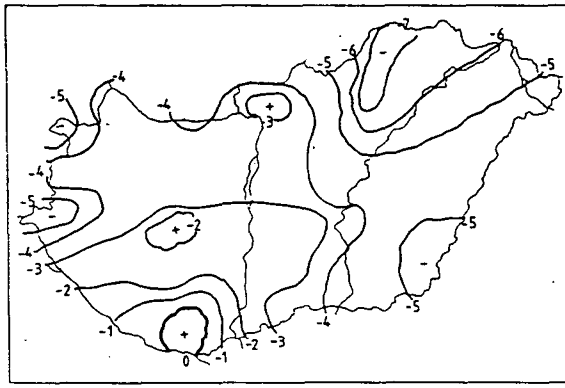

Fig. 4. Areal distribution of the Mediterranean index in Hungary (1901—50)

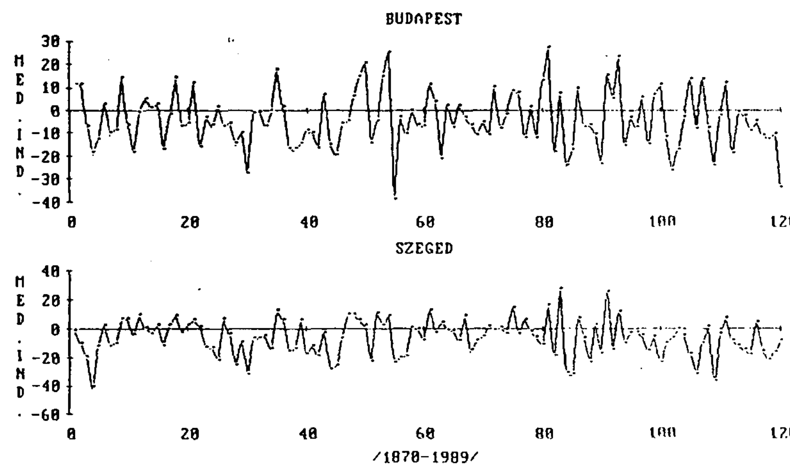

Fig. 5. March of the Mediterranean index in Szeged and Budapest (1870—1989)

Further, we surveyed the *120*-year (*1870-1989*) precipitation series of Budapest and Szeged. We counted up the values *MI* station by station and year by year so as to investigate the alternations of the Mediterranean and the continental effect. The way of walking of the *MI* is demonstrated on a chart in *Fig. 5*. It is visible that the fluctuation according to years is very great in both directions.

We have determined the proportions of the years with positive or negative indexes broken down according to *10* years, as well as in the relation of the whole *120*-year series (*Table III*). It is visible that with both stations the years with positive values occur in their entirety approx by a ratio of *1/3*; while with the *10*-year phases, the variety is great. (From *10%* to *60%*.) We also looked at how many times in the cases of the two stations indexes with identical signs occur in the same years. On the whole, approx in *1/6* of the cases the values are positive simultaneously; while in more than half of them they are negative simultaneously; that is in precisely *71·7%* of the cases the *MI* has identical signs.

Table III

The numbers and the proportions of the years with positive and negative Mediterranean indices in every 10 years and between 1870 and 1989 in Szeged and Budapest

	Szeged		Budapest		Sz—Bp	Sz—Bp
	+	-	+	-	++	--
1870—79	3	7	4	6	2	5
80—89	6	4	4	6	3	3
90—99	3	7	2	8	1	6
1900—09	3	7	2	8	2	7
10—19	4	6	4	6	3	5
20—29	4	6	2	8	2	6
30—39	3	7	4	6	1	4
40—49	4	6	5	5	1	3
50—59	4	6	3	7	3	6
60—69	2	8	5	5	2	5
70—79	1	9	2	8	—	7
80—89	2	8	1	9	1	8
Sum total	39	81	40	80	21	65
%	(32·5)	(67·5)	(33·3)	(66·7)	(17·5)	(54·2)

For further investigation of the closeness of the connection between the characters of the precipitation marches of the two stations, we calculated the correlation coefficient of the MI values. The coefficient happened to be $r = 0{\cdot}5808$, which even on a *1%* significance level relates to a very close connection with an identical sign (the critical value, in case of *120* pairs of value, is $p^{1\%} = 0{\cdot}23$). Thus, in the *120*-year precipitation series of the two stations, the years having either a Mediterranean or a continental character, as well as the order of magnitude of the indexes of these alternate in a rather identical manner.

With a view to the exploration of the possible periodic recurrence, we investigated the *120*-year *MI* series with the method of the Fourier analysis.

Having sorted the time series according to the presumed periods of T = *2—61* years, we detected the constants of the equations

$$y = A \sin(2/\pi x/T + U).$$

(A = amplitude, T = length of period, x = time in years, U = phase angle.) The amplitudes resulting have been expressed in the ratio of the expectancy $E = \sigma(\pi/n)^{½}$. (σ = standard deviation of the data, n = number of the members of data).

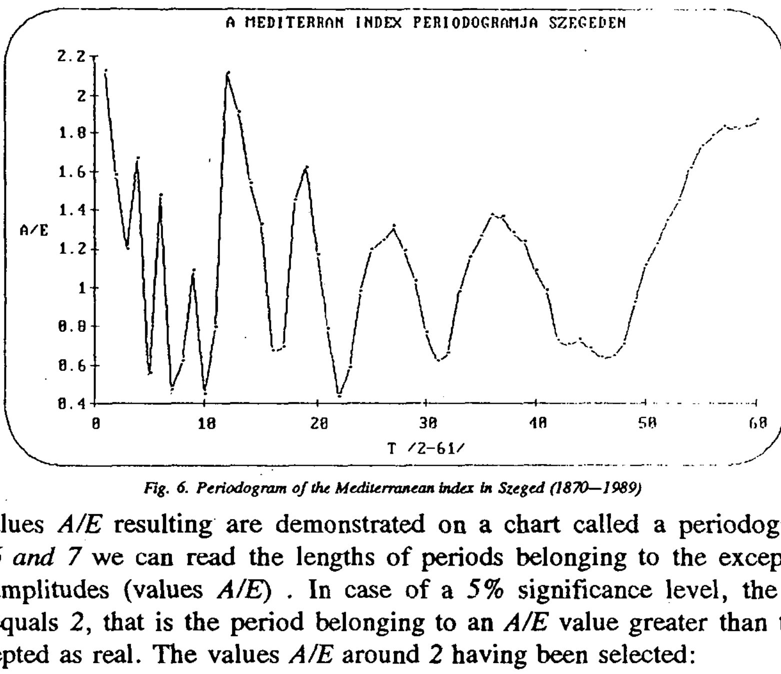

Fig. 6. Periodogram of the Mediterranean index in Szeged (1870—1989)

The values *A/E* resulting are demonstrated on a chart called a periodogram. In *Figs. 6 and 7* we can read the lengths of periods belonging to the exceptionally great amplitudes (values *A/E*) . In case of a *5%* significance level, the critical value equals 2, that is the period belonging to an *A/E* value greater than this can be accepted as real. The values *A/E* around *2* having been selected:

In the case of Szeged,

the *2-year (A/E = 2·19)*,
13-year (A/E = 2·11),
and *14-year (A/E = 1·90)* periods,

in the case of Budapest,

the *8-year (A/E = 1·82)*,
and *15-year (A/E = 2·14)* periods look real.

Further on, we looked for a connection between the anomalies of the Mediterranean index and those of sea-level pressure. We considered the pressure series of *17* European and Mediterranean-region stations in the relation of the years between *1951* and *1980*, broken down from month to month. The difference between the amount of the October and November anomalies (with signs) and the amount of the May and June anomalies was calculated for every single year in mbs,

$$LA = \Delta p(X+XI) - \Delta p(V+VI).$$

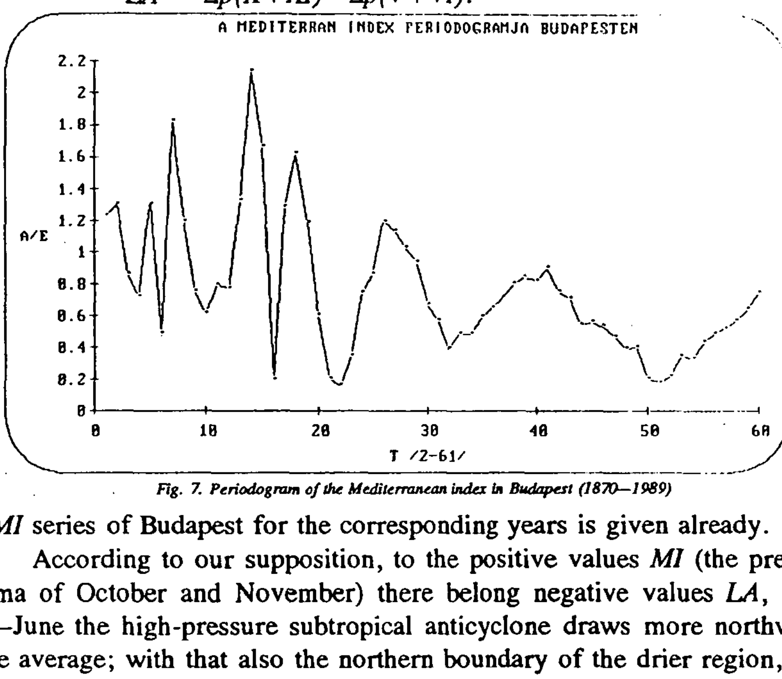

Fig. 7. Periodogram of the Mediterranean index in Budapest (1870—1989)

The *MI* series of Budapest for the corresponding years is given already.

According to our supposition, to the positive values *MI* (the precipitation maxima of October and November) there belong negative values *LA*, that is in May—June the high-pressure subtropical anticyclone draws more northward than on the average; with that also the northern boundary of the drier region, and vice versa.

By the help of the correlation coefficient, we looked at which regions are those to which there belong *LA* values between which and the Budapest *MI* values a contrary march is positively demonstrable. In case of *30* pairs of data, the *5*, *1*, as well as *0·1%* significance levels are

$$p_{30}^{5\%} = 0{\cdot}3494,\ p_{30}^{1\%} = 0{\cdot}4487, \text{ and } p_{30}^{0.1\%} = {\cdot}0{\cdot}5541.$$

The correlation coefficients resulting are illustrated in *Fig. 8* on a chart; the negative values amounting to an at least *5%* level, framed. As was to be expected, the marches of the *MI* and *LA* opposite in meaning compared with one another are mainly characteristic of stations of the Mediterranean region.

Having performed the calculation corresponding to the preceding one besides Budapest for Szeged as well, we get a similar result. The correlation coefficients calculated are to be found in *Table IV*.

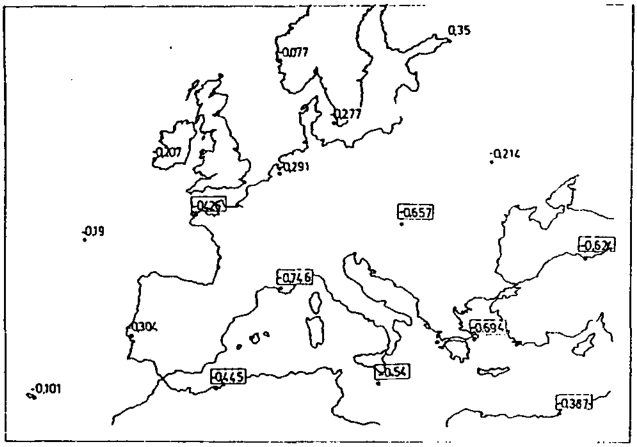

Fig. 8. Areal distribution of the correlation values between the mediterranean index in Szeged and the anomalies of air pressure in case of some station

Table IV

Correlation values between the mediterranean indices
and the air pressure anomalies of the listed stations (1951—80)

	Budapest	Szeged
Bergen	-0·077	0·054
Valentia	-0·207	-0·197
De Bilt	-0·291	0·017
Copenhagen	-0·277	-0·290
St. Petersburg	0·350	0·051
Kiev	-0·214	-0·560
Ship K	-0·190	-0·115
Brest	-0·426	-0·300
Marseille	-0·746	-0·550
Budapest	-0·657	-0·766
Samsun	-0·624	-0·618
Funchall	-0·101	-0·280
Lisboa	-0·304	-0·343
Oran	-0·445	-0·402
Malta	-0·540	-0·430
Athens	-0·694	-0·588
Alexandria	-0·387	-0·215

Consequently, in the years in which the subtropical anticyclone is well developed in early summer (a negative *LA*), in the precipitation march of Hungary, the Mediterranean character prevails, (an autumnal precipitation maximum — a positive *MI*), while in case of a weak anticyclone in early summer (a positive *LA*), it is the continental character which comes to the fore. (An early summer precipitation maximum — a negative *MI*.)

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